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REPORT OF THE EIGHTEENTH SESSION  
GREAT BRITAIN 1948



PART III (3)

PROCEEDINGS OF SECTION B  
METASOMATIC PROCESSES IN  
METAMORPHISM

LONDON  
1950

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*General Editor : A. J. Butler*

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PART III

PROCEEDINGS OF SECTION B  
METASOMATIC PROCESSES IN  
METAMORPHISM

*Edited by*

ARTHUR HOLMES and DORIS L. REYNOLDS

LONDON  
1950

**Section B, Metasomatic Processes in Metamorphism, met  
on three occasions during the Session. The successive Chairmen  
at these meetings were as follows :—**

<b>August 26th</b>	<b>Professor Arthur Holmes</b> <b>Professor H. H. Read</b>
<b>August 28th</b>	<b>Professor C. E. Wegmann</b> <b>Professor E. S. Larsen, Jr.</b>
<b>August 31st</b>	<b>Professor Pentti Eskola</b> <b>Professor H. von Eckermann</b>

**The Secretary of the Section was Dr. Doris L. Reynolds.**



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# THE NATURE OF METASOMATISM IN THE PROCESSES OF GRANITIZATION

By PENTTI ESKOLA

Finland

## ABSTRACT

Several kinds of sedimentary and igneous rocks show gradual transition into granites in a manner indicating metasomatism. Very common is the granitization of metamorphic rocks of argillaceous origin. They are mostly first converted into migmatites and successively into almost homogeneous granites with faint "nebulitic" relict structures. The chemical change into ideal granite implies addition of  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  and subtraction of  $(\text{Fe}, \text{Mg})\text{O}$ . Quartzites are granitized by addition of all the oxides present in granite except  $\text{SiO}_2$ . Thus the change would seem to be addition of the other oxides only, but the succession of the transitional types, beginning with veined quartzites, is best accounted for by the assumption that the added material was granitic magma and that some silica was carried away. Granitization of limestones is of rare occurrence and is a very complicated process in which certainly all the elements of granite except lime must have been added and in the net result lime subtracted. The final stage in this case also appears to have been reached by the mass action of granitic magma which soaked into the rock. Very clearly this has been the case in the granitization of older, mostly gneissose, igneous rocks of more basic composition, such as diorites. This is the most commonly observed case of granitization in the Archæan and it can be followed by steps in the gradual transition series, microscopical observation as a rule indicating injection of granitic material, presumably as pore-magma, between the grains of the older rock. The final product, an ideal granite, appears to be deprived of most of its original  $\text{Na}_2\text{O}$ ,  $\text{CaO}$ , and  $(\text{Mg}, \text{Fe})\text{O}$ .

Characteristic of the metasomatic granitization is the constant occurrence of intermediate stages and of relict structures from earlier stages, whereas such features are entirely lacking in those granites that otherwise prove to have crystallized from liquid magmas, such as the rapakivi, the synkinematic differentiated intrusives (the "urgranites" of Sweden), or the graphophyric granites differentiated from dolerites. The fact that the bulk composition of such granites, whose magmatic origin is beyond any doubt, may be identical with that of granites derived from, say, sediments, is in itself a strong evidence for the notion that liquid magma has been the source of material in all cases.

Though there are evidences of subtraction of material as well as of addition, so that the term metasomatism is justified, the change certainly has not occurred at constant volume, but swelling up into domes and upward intrusion have been invariable features in connection with granitization. This is what may be expected from our conclusion that the granitizing agent or ichor was granitic pore-magma pressed upwards or forwards in the earth's crust during tectonic movements.

**A**LTHOUGH granites show considerable variation in composition, there is nevertheless a certain rather limited range of variation that every petrologist will regard as especially typical of granites. The usual composition is characterized by potash predominant over soda, the analyses showing from about 5 to 7 per cent  $\text{K}_2\text{O}$  and from 2 to 3 per cent  $\text{Na}_2\text{O}$ .  $\text{SiO}_2$  varies from about 68 to 75 per cent,  $\text{CaO}$  from 1 to 3 per cent.  $\text{FeO}$ , in maximum some 4 per cent, is invariably in excess over  $\text{MgO}$ . I propose to call rocks of such composition *ideal granites*.

The genetic significance of the ideal-granitic composition will be revealed if we inspect the granitic rocks grouped according to their connection with the phases of orogeny and their genetic provenance, either magmatic or metasomatic. Among all Finnish intrusive rocks containing more than 68 per cent  $\text{SiO}_2$  about a half are ideal granites, but in one tectonic group, the synkinematic (or synorogenic) granites, which are generally of purely magmatic origin, the ideal granites are very rare, whereas in all other groups, as we will see presently, the ideal granites are in overwhelming majority.

Many dolerites, which are strictly anorogenic magmatic rocks, are cut by granitic veins, as a rule graphophyric (granophyric according to the rather unfortunate term of Rosenbusch). Such felsic veins in the post-Jotnian olivine-dolerite in South-West Finland, near the contacts, are at many places apparently paligenic, crystallized from magma formed through selective anatexis of the adjoining



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rock, which may be either Jotnian sandstone, rapakivi, or Archæan migmatite. The paligenetic veins now appear as apophyses from the country rocks. In other instances similar veins are probably products of direct crystallization differentiation from the dolerite magma. Their composition is variable. Often they are highly sodic, sometimes of an alkaline character. In any case they are products of crystallization from liquid magma, and even a most ardent advocate of the metasomatic theory could hardly insist that in this case granitic rocks have originated in a metasomatic way. Yet they are frequently ideal-granitic in composition, as seen from analysis of a graphophyre from Säppi Island (analysis 1) in Gulf of Bothnia.

The rapakivi rocks of Fennoscandia are postkinematic granites of mainly ideal-granitic composition (analysis 2). There is evidence of magmatic differentiation in the rapakivi provinces and the rocks are most typical magmatic rocks, as appears, among other things, from the absence of any relict features of earlier structures such as are characteristically present in metasomatic granites, and from the fact that they are connected with and show textural transition into effusive rocks, such as quartz-porphyrries, of ideal-granitic composition (analysis 3). In any case they must have attained their composition before being emplaced. The rapakivi rocks thus represent the liquid line of descent in magmatic differentiation.

The synkinematic granites also are purely magmatic rocks, but they belong to a richly differentiated series, beginning from basic oldest members. Variation diagrams constructed from any synkinematic intrusive series show all the characteristics of differentiation diagrams. The youngest members contain alkalis in variable proportions, in some provinces passing into soda-rich trondhjemites, but more often into granites with intermediate feldspar proportions. Ideal-granitic composition may also be reached, though rarely (analysis 4). More often the variation diagrams indicate a trend towards the ideal granite, but the differentiation appears to have been arrested before the goal was reached. In all these cases the development of the chemistry of the rocks may be accounted for by the crystallization differentiation theory. The normal course towards ideal granite may have been diverted by some early event in the magmatic history, as by diffusion of water from invaded sediments in the case of trondhjemites, according to V. M. Goldschmidt; or by assimilation of foreign materials. Failure to reach the ideal-granitic composition may also have been due to deficiency of potash in the initial magma.

So far I have spoken only of the genesis of granite by crystallization differentiation. This seemed appropriate in order to stress the fact to which I am now coming, namely, that the genesis of metasomatic granite may lead to a rock chemically identical with magmatic granites. In fact the composition that I have termed ideal-granitic is still more common among granites of metasomatic origin.

As mentioned above, truly magmatic granites representing end-products of differentiation are rather rarely ideal-granitic among the synkinematic intrusions. During detailed mapping in Finland in the last few years it has been repeatedly found that ideal granites in connection with these have been formed by the soaking of granitic material into more basic rocks. The change may often be followed in the form of gradual transition, beginning with injection or impregnation with narrow veinlets or simple grains of microcline and quartz, first filling the spaces between the older grains and eventually resulting in a complete replacement of all the constituents that do not belong to the ideal granite. The change shows all the features of metasomatism in its net result, that is to say replacement of Na, Ca, and (Mg,Fe) by K and Si. Although it may be chemically complete so as to obliterate the specific minerals of the more basic rock, like anorthite-rich plagioclase and hornblende, some textural features are usually left as relics, such as a gneiss-like arrangement of biotite in an otherwise unorientated granitic fabric. A certain veined appearance is also commonly present, indicating that the new material has invaded the rock along paths of least resistance (analysis 5).

Among the best examples of granitization of synkinematic diorites are those found at the classical localities described by J. J. Sederholm in his studies on anatexis and paligenesis. Basaltic dikes have been intruded along fissures in diorite which has later been granitized and become intrusive anew, brecciating the basic dikes. The evidence is very convincing, as the change may be followed through



different stages. Where the diorite shows no trace of granitization, the metabasaltic dike remains intact. Following the dike into a granitized area one may observe first small apophyses of granite in the metabasalt, and finally there are just rows of inclusions left. Such phenomena are well illustrated by the sketch-maps that Sederholm has published in his memoirs.

In my memoir of 1914 on the Orijärvi Region I described a synkinematic suite of intrusions, calling the most acid member of the series oligoclase-granite. In my description I mentioned that at a few places the oligoclase-granite passes over into reddish varieties richer in microcline, believing them to be the latest differentiates. At a revision of one of these localities last year I found, however, that here also metasomatic granitization has been at work. The red rock is ideal-granitic in composition and almost aplitic in texture, but it still shows an inherited parallel orientation of streaks of mica like the primary granodioritic rock.

*Analyses of Ideal Granites*

	M a g m a t i c				M e t a s o m a t i c			
	Anorogenic	Post-kinematic		Synkinematic	Synkinematic		Late-kinematic	
	1	2	3	4	5	6	7	8
	Graphophyre in dolerite Säppi	Rapakivi Laitila	Quartz-porphry Gulf of Bothnia	Granite-gneiss Liusvaara	Granite-gneiss Eckerö	Matrix, orbicular rock Kangasniemi	Granite Kakola	Granite Hangö
SiO <sub>2</sub>	74.99	70.42	72.46	71.84	74.17	74.54	73.56	71.75
Al <sub>2</sub> O <sub>3</sub>	10.04	13.22	13.04	13.56	12.78	12.59	14.72	14.13
Fe <sub>2</sub> O <sub>3</sub>	0.91	0.64	0.56	0.87	1.80	0.80	0.39	1.12
FeO	2.44	3.74	2.55	1.37	0.59	1.44	0.75	1.13
MgO	0.76	0.07	0.26	0.70	0.29	0.47	0.20	0.64
CaO	0.48	2.27	0.72	1.16	0.74	1.06	0.83	1.59
Na <sub>2</sub> O	2.24	2.81	3.03	2.96	3.38	2.68	2.99	2.25
K <sub>2</sub> O	6.79	5.21	6.02	6.02	5.14	5.86	5.78	5.85
TiO <sub>2</sub>	0.28	0.52	0.37	0.44	0.26	0.21	0.11	0.18
MnO	0.12	0.04	0.01	0.01	0.03	0.04	tr.	tr.
P <sub>2</sub> O <sub>5</sub>	0.09	0.09	tr.	0.19	0.19	0.00	0.03	0.07
H <sub>2</sub> O+	} 0.93	0.63	0.98	0.34	0.63	0.39	0.56	} 0.83
H <sub>2</sub> O—		0.09	0.05	0.12	0.16	0.09	0.28	
	100.07	100.45*	100.05	99.63	100.16	100.17	100.20	99.78

\* Total includes BaO, 0.13; ZrO<sub>2</sub>, 0.11; F, 0.46%.

Illustrative examples of the granitization of more basic rocks like granodiorites, quartz-diorites, and quartz-monzonites are found in many orbicular rocks (called *esboites*, Eskola 1938). Their orbicules, of varying composition, though always containing zones mainly composed of oligoclase, are embedded in a paligenic ideal granite enclosing "ghostly" remnants of the more basic rock (analysis 6). There is ample evidence that the orbicules started to crystallize in the basic rock in a solid state at the same time as granitization set in, relics of the primary matrix being still preserved.

Where the granitization of the synkinematic intrusives has been complete, the rocks are texturally like the late-kinematic (or late-orogenic) granites save for the presence of relict gneissose structures.



The late-kinematic granites in Fennoscandia are, in general, largely of palingenic nature. It was from them that Sederholm developed his ideas of granitization, migmatization, anatexis, and palingenesis.\*

Among the granites of the late-kinematic group one may find evidence of granitization of rocks of widely different types, such as the synkinematic intrusives mentioned above, acid volcanics, argillaceous and arkosic sediments, and quartzites. Some authors in Finland nowadays use the word palingenetic granite almost as a synonym for late-kinematic.

Probably best adapted to granitization are the residual sediments which, in metamorphic dress, appear as mica-schists or para-gneisses. Such pronouncedly schistose rocks are generally first changed into migmatites of the kind known as veined gneisses, consisting of newly introduced granitic or pegmatitic veins and gneissic schlieren representing the older portion of the rock. With progressive homogenization the gneissic schlieren become more and more confused, but they rarely disappear entirely. Even in the most homogeneous-looking granites of this kind there are "ghostly" remnants of well-digested and assimilated older rock, now appearing in the form of vaguely orientated schlieren richer in biotite.

Another important result of the detailed mapping in Finland is the recognition that cordierite-almandite-gneisses, or kinzigites, compose a great part of the Archæan crustal rocks. In the Svecofennian territory of South-West Finland the kinzigites are invariably migmatized in the manner of veined gneisses, but their "veins" are mostly blind, lenses or patches, and the pegmatite material in them also contains cordierite or almandite. As this migmatite does not differ in its bulk composition from ordinary clayey sediments and as its gneissic portions sometimes show relict varve structures, the conclusion is close at hand that the veins have segregated from the rock itself with no addition of foreign material. Thus these migmatites represent *venites*, as defined by P. J. Holmquist, who explained them as products of ultrametamorphism with no injection of new magma. In fact, Holmquist had been led to that conclusion precisely by the study of similar kinzigites in the Stockholm region. Besides the venitic segregations there appear more sharply bounded longer veins of reddish pegmatite, often cross-cutting. In the migmatites of South Finland first studied by Sederholm such veins are more conspicuous than those in the kinzigites. Sederholm therefore concluded that the veins in migmatites were formed from new granitic magma injected into the rock from outside and he called such veined gneisses *arterites*. The years-long debate on this question between Sederholm and Holmquist resulted in the realization that both were right. Even in some kinzigite migmatites the addition of new material has been very great, as they may contain up to 90 per cent ideal-granitic material which is far above the amount that could be derived from the original clayey material.

As is the general rule in migmatization, the kinzigites may also become perfectly homogenized into massive granites. A splendid example is the Kakola granite in the town of Turku in South-West Finland (analysis 7). Cordierite-rich migmatites are seen to grade over into granite containing disseminated lumps of cordierite and almandite. Analyses of the Kakola granite differ from normal ideal granites only in having a slight excess of alumina which can be detected only by calculation. According to Hietanen this analyzed rock contains 12.5 per cent kinzigitic and 87.5 per cent granitic material.

The palingenic granites of widest distribution in South Finland seem to be derived from acid volcanics, or their metamorphic derivatives, leptytes, or from arkosic sandstones. They include medium

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\* Here I would like to add a remark about terminology. In his *Meditations on Granite*, H. H. Read says, that of the two terms *anatexis* and *palingenesis* one is superfluous, and he would drop palingenesis. This sounds to me rather unexpected from Read. Palingenesis refers to rocks, and is a neutral term, whereas anatexis means re-fusion or remelting, the term in itself being a manifestation of Sederholm's altogether plutonistic standpoint, though it is quite true that he was not at all consistent in the use of the terms. Thus rocks may be palingenetic after anatexis or any other process, e.g. metasomatism, whereas only a magma can be anatectic. (H. H. READ, *Meditations on Granite*, *Proc. Geol. Assoc.*, 54, 1943, p. 64; 55, 1944, p. 45.)



and even-grained granites with "ghostly" relics, as the Hangö granite (analysis 8), and coarse-grained porphyritic granites of similar composition.

Quartzites may become granitized in different ways. The commonest, or at least the one best known to me personally, is much like that of the mica-schists, the first stage being veined quartzite. In this the quartzitic schlieren are impregnated with feldspars at an early stage and the further development does not differ from that of the veined migmatites described above, the final product, as a rule, being ideal-granitic. It is a matter of course that, in cases where the original rock was pure quartzite, the granitic or pegmatitic veins must be altogether introduced material, *i.e.*, the quartzite migmatites are true arterites. Such migmatites occur on a large scale within the Karelidic territory of North Finland.

Among all common rocks the limestones are most resistant to granitization. In Finland it is an old experience that even in granite-invaded territories where all other rocks have succumbed to the migmatizing agencies the limestones remain intact. They are, moreover, capable of protecting their nearest country-rocks, as the limestone layers are usually surrounded by layers of leptites. Granitic material comes into contact with the limestone only as cross-cutting dikes which surely are mechanical intrusions filling opened fissures rather than replacement veins. Only where limestone is first converted into skarn by pneumatolytic metasomatism may this eventually become granitized in the same manner as other basic silicate rocks.

Skarn, however, is also very resistant to granitization, and it is on only a small scale that such changes can be detected. Lime-rich silicates, such as andradite or hedenbergite, are first converted into dark hornblende, which in turn alters into biotite which is eventually disseminated through introduced granitic material. The same is true of basic magmatic rocks like peridotites or gabbros.

The chemical changes involved in granitization are of course always apparent in the net results. It has been supposed by the advocates of granitization by metasomatism in solid rock that only the elements or ions necessary in each case to transform the rock into granite have been added. Thus, in the granitization of quartzites all the granite elements except Si should have been added, in the case of limestones all but Ca, whereas clayey sediments would need only K and Si, or potassium silicate. As in one case one set of elements and in another case other elements are needed to transform a rock into granite, yet all rocks get what they need, it is for me hard to see why it should not be assumed that the granitizing agent has been granitic magma. It would seem from the above brief summary of the granitization of different rocks that the succession of events, as recorded by transitional types such as veined gneisses, is best accounted for by the assumption that this has been actually the case.

Many authors have in the last few years advocated with great enthusiasm the idea that granites have been mainly formed by metasomatism in the solid state without magma or any liquid medium whatever. I would like in this matter to follow the words we find in Paul's first Epistle to Thessalonians: "Quench not the spirit. Despise not prophesyings. Prove all things and hold fast that which is good." So I have tried to prove the said ideas. Being one of the first to assume metasomatism in silicate rocks without the mediation of magma I can hardly be blamed for predisposition against those ideas. So first I have to say that there are lots of good things in them.

The metasomatic and antimagmatic theories of granitization have arisen as a reaction against the crystallization-differentiation theory which has been epoch-making for petrology, placing our science for the first time upon a firm physico-chemical foundation. As in any human work there may be errors in the premisses or applications of this theory. It is wholesome that a system of thought should be vigorously shaken once in a while so as to prevent it from stiffening and becoming an obstacle to free progress. The history of geology offers numerous examples of dangers arising from canonization of doctrines elaborated by eminent men who have led science upon new trails—we may only recall Werner or Rosenbusch. But the history of geology also provides almost as many examples of exaggeration and at last of similar dogmatism from the side of those who dared to break away from the authorities—here we may recall von Buch.

### PART III : METASOMATIC PROCESSES IN METAMORPHISM

So, I have tried to prove the modern, already very diversified, theories of metasomatic granitization and have become convinced that both things just mentioned are happening. It is out of question here to discuss all of them, most tempting as it would be, *e.g.*, to scrutinize H. H. Read's inspiring *Meditations* which, I think, is the most skilful and diplomatic apologia so far presented for the said theories. From amongst Read's many aphoristic sayings I just want to pick up two which have bearing upon my present topic.

One is Read's statement that granites and basalts are different things. This, I think, is a true and fruitful idea, now ripe to be generally pursued. It is also consistent with experimental and geological data established since I published my paper on the origin of granitic magmas. The problem is connected with that of the origin of the Sial crust (Eskola, 1945).

With the point of another frequently repeated aphorism in Read's address, "There are granites and granites", on the other hand, I cannot agree, if he means that some granites have come into existence without the mediation of liquid magma, while others may be magmatic. Although the mechanism of granitization has been largely that of metasomatic replacement, yet it has been effected by the action of magma, and the conditions have been those of crystallization of residual liquids which, under ideal conditions of PTX, leads to an ideal granite, representing the lowest points of the solidus in the polycomponent system of the granite elements. Only thus can be understood the fact mentioned at the outset in this paper, namely, that the same composition results from both the primary magmatic and the metasomatic crystallization.

The problem is similar to that of metamorphic recrystallization: whether it has happened by means of reactions in the solid state or by the mediation of water. Reactions do take place in solids, but some water has been present during metamorphism, as hydrated minerals are generally formed. Water is an influential promoter of reactions. Why then deny its action? In the same way we know that quartz and feldspars and many other silicates can be formed without the action of magmas, *e.g.*, by hydrothermal metasomatism; but we also know (a) that granites can be formed by crystallization from mutual silicate solutions, or magmas, and (b) that the solidus-temperatures of granites are somewhere below 600°C., *i.e.*, within the range actually obtaining in those regions of the lithosphere where the highest grades of metamorphism pass over into anatexis and palingenesis of granites. According to the results of R. Goranson the end of the magmatic crystallization is rather sharp. After that the residual hydrothermal solutions mainly contain silicic acid that crystallizes in the form of quartz. In good accordance with this is what may be observed at any migmatite front: where migmatites with granitic veins die out, the latter are succeeded by numerous quartz veins in the schistose rocks. Considerable quantities of non-volatile elements are contained in the residual aqueous solutions only in exceptional cases, in the presence of certain carriers, such as alkaline solutions with alkali silicates (water-glass), carbonic acid with bicarbonate solutions which may account for the formation of alkaline rocks in some cases, sulphur compounds, etc., giving rise to ore deposits, and other exceptional mineral assemblages, but they are probably of no concern in connection with the genesis of granites.

If the temperature conditions obtaining during granite metasomatism were different from those of the solidus conditions of granitic magmas, the products could hardly be the same. Metasomatism means crystallization of those phases that are least soluble under the given conditions, *e.g.*, in magnesia metasomatism. Magmatic crystallization of granites, again, means solidification of the residue in which the mutual solubility is realised at the lowest temperatures possible. This residue has, in a given system, a constant composition. It is this fact alone that makes it conceivable why the composition of the granites varies within such narrow limits as it does.

My thesis is therefore that all granites are magmatic. It is, then, a matter of secondary interest whether the magma has been solidified directly or by metasomatic replacement of earlier rocks according to the law of mass action.

It is not conceivable that huge homogeneous rock masses of granitic composition could be formed



through metasomatism by addition of elements in diluted solutions, or as atoms wandering in the solid rocks. In fact the apparent hydrothermal or pneumatolytic metasomatic rocks like skarns or cordierite-anthophyllite-rocks are just strikingly non-homogeneous. So are also acid silicate rocks of metasomatic origin like sericitic ore-quartzites, or greisens near the tin-ore veins. Their composition is, moreover, irregularly variable and never approaches that of granites. Nor are the feldspar-bearing rocks formed by hydrothermal replacement with alkali silicates, apparent in numerous different cases, limited in their variation as are the ideal granites. Locally replacement frequently leads to almost monomineralic products. Sodium is the more mobile of the common alkali metals and soda metasomatism produces many kinds of albite-rich rocks of irregularly variable composition, such as helsinkites, fenites, adinoles, and spilites. The soda-extreme leptytes and the soda-rich boundary varieties of many synkinematic granodiorite plutons are probably also products of soda metasomatism. Potash metasomatism is known from the sanidinites. Recently a very remarkable replacement of anorthite-rich plagioclase in basaltic volcanites has been described by W. P. De Roever from Celebes. The potash-extreme leptytes of Sweden, often nearly monomineralic microcline rocks, have probably also been formed by potash metasomatism.

As important evidence for the non-magmatic nature of metasomatism in granitization Read cites the occurrence of rapakivi ovoids in the country rock, and of big "porphyroblasts" of potash feldspar in schists, saying that therefore "we must query the magmatic status of the rapakivi granite itself" as well as of porphyritic granites in general. These phenomena do not bother me in the least. Why could not big crystals grow out from the pore-magma permeating the rock? The physico-chemical controls, contrary to Read's belief, do in fact "operate also in the country rock environment exactly in the same way as they did in the consolidating magma" (*Meditations* II, p. 76). The country rock here takes no part in the reactions in the magma, it does not belong physico-chemically to the system in operation.

Rapakivi being in question I would here like to refer to another feature of the rapakivi contacts where ovoids usually occur in the country rocks. I mean the zone of contact breccias or, as Wegmann terms it, "the agmatite front." In 1905, when I commenced my rapakivi studies, I made a sketch of a magnificent outcrop of such a breccia at the Laitila rapakivi contact. The adjoining gneiss has been broken into innumerable fragments which have been vigorously disturbed and turned into all possible positions. There can be no talk about quiet replacement, atom by atom, without disturbance of the old structure. This, of course, would not bother Wegmann or Backlund, and perhaps not Read. They could, also, refer to the breccias of the Rhine volcanic vents, investigated by Hans Cloos who has demonstrated that there have been no violent explosions and no eruptions of lava. The brecciation has been effected by placidly boiling steams only. But consider the contrast between the breccia and the rapakivi. The latter retains its typical texture up to the very contact and even in the breccia, showing that tranquility of structure which is so characteristic of the rapakivi, with no signs of the movement that is so strikingly manifested in the breccia. The rapakivi must have crystallized exactly at the place it now occupies. It is a postkinematic pluton. At such a contact, Hutton's words quoted by Read (*Meditations* I, p. 68) appear to be literally true: "Without seeing the granite actually in fluid state, we have every demonstration possible of this fact: that is to say of granite having been forced to flow, in a state of fusion, among strata broken by a subterranean force."

Finally a word must be said about the space problem in which the antimigmatists find one strong argument, insisting that granitization has normally occurred at constant volume. This has certainly not been the case. Swelling up into domes and vertical or horizontal intrusion are invariable features in connection with the granitization of older masses, as may be expected from our conclusion that the granitizing ichor was pore magma pressed upwards and forwards in the earth's crust, normally in larger amounts than the materials expelled during the replacement.

I believe that the physico-chemical foundation of petrology laid by Bowen, Niggli, Goldschmidt and others will last. Many of the advocates of the present day metasomatic school are likely to throw away the baby with the bath-water when wanting to eliminate magma or to replace it by something



### PART III: METASOMATIC PROCESSES IN METAMORPHISM

that is beyond the possibility of experiment or observation. But I also believe that the spirit of this school will result in fair progress of our science when once its exaggerations are recognized and avoided.

#### DISCUSSION

THE CHAIRMAN, A. HOLMES, said he was sorry to find himself in complete disagreement with his old friend Professor Eskola on the question of the capacity of granite-magma to bring about the phenomena of granitization. In the geological settings under consideration he would regard granite-magma—where there is reason to think that it has existed—as the culminating effect of granitization, and not as the cause of granitization. The difference of opinion between the schools of thought to which Professor Eskola and the speaker belonged was, he thought, fundamentally psychological in its origin and persistence. Professor Holmes said that as a student he had acquired a highly dogmatic belief in granite-magma, a belief entirely unsupported by evidence, but backed by a great weight of authority. Since then, in the light of his own experience and that of others, he had gradually abandoned the hypothesis that granite had resulted from the crystallization of magma. The difference between them was that Professor Eskola still retained the faith in which he had been brought up, whereas the speaker had completely lost that faith.

SIR LEWIS FERMOR said that in his wide experience of the vast granitic tracts (often somewhat gneissose) of Peninsular India he had seen no reason to treat these granitic rocks as anything but the products of crystallization from intrusive magmas. But, accepting that some granites might have resulted from “metasomatic” replacement of other rocks, it was interesting to notice from Professor Eskola’s paper that in Finland the source of the replacing substances was to be regarded as liquid magma, presumably also of granitic composition.

A study of the analyses of Professor Eskola’s ideal granites showed that in only one constituent was there any constant difference between his magmatic and his metasomatic granites, namely that in his three magmatic granites the total content of iron oxides was in each case greater than the total iron oxide content of the four metasomatic granites. The speaker wondered if this difference was accidental or significant. He wished also to note that those who spoke of “metasomatic” granites did not appear to be using the term in its customary significance according to which the volume of the final product should be about equal to that of the rock or mineral replaced.

DORIS L. REYNOLDS said there were several questions she would like to ask Professor Eskola. As he had just told them, Fe, Mg and Ca were amongst the common constituents that were removed from rocks during granitization. How did Professor Eskola suppose that granite magma, which he considered to be the agent of granitization, was able to remove the Fe, Mg and Ca, and what did he think became of these constituents?

Dr. Reynolds supposed that they would all agree that quartzite and limestone were amongst the rock types that were relatively resistant to granitization. If granite magma were the agent of granitization then ease of granitization must have depended on ease of penetrability. The bedding planes of pelitic rock types provided divisional planes along which such magma had been supposed to penetrate, and it was true that quartzites and limestones would split less easily in that way. But both quartzites and limestones were characteristically well jointed, and divided by other types of structural breaks, all of which would provide pathways along which granite magma might be supposed to penetrate. Why then, if granitization depended on injection of granite magma, were quartzites and limestones so resistant to granitization?

Professor Eskola appeared to regard the fact that each rock received just what it required to convert it to granite as a difficulty in the way of accepting solid diffusion as the mechanism whereby granitization was effected. It was, however, a fact that when pyroxene was converted to amphibole only those elements necessary for the change were fixed, and in that small-scale example of transformation, there could be no doubt that ions and not magma entered the pyroxene.

P. E. ESKOLA in reply to Dr. Reynolds, said that quartzites, especially schistose varieties, were quite easily granitized, veins of granite being intruded and the veined quartzites eventually homogenized. Basic or ultrabasic plutonic rocks offered greater resistance against granitization and still more the limestones. That appeared to be due to their physical consistency, their relative impermeability to the granitic magma.

To the second question of Dr. Reynolds: How to account for the removal of CaO, etc., if the metasomatism were caused by injected granitic magma, he replied that it is not possible to tell where those substances went when they disappeared, but the same was true regarding any kind of metasomatism which was controlled by the law of mass action.

C. E. TILLEY raised the question as to whether there is a volume change during granitization.

B. C. KING said that volume changes during granite emplacement appeared to relate more closely to tectonic environment than to the possible consequence of granitization. Syntectonic bodies included, at the deepest levels, those—usually clearly of replacement origin—in which the comparative lack of displacement in the invaded rocks was reflected in the character of the abundant relic structures, as well as, at higher levels, those partly allochthonous masses in relation to which upthrusting and lateral displacement of the adjacent rocks were commonly apparent.

Post-tectonic bodies, among which were to be numbered the greatest batholiths, were in general sharply discordant to the invaded rocks. Since evidence from the most deeply eroded terrains suggested that bodies of such dimensions did not persist to the greatest crustal levels susceptible to direct observation, it was likely that the great batholiths were not “bottomless” and only become “integrated” at higher levels.

## ESKOLA : NATURE OF GRANITIZATION

Hypotheses of mechanical displacement of the pre-existing rocks, even by piecemeal stoping, were therefore regarded as untenable, so that even those bodies must have developed by replacement and without considerable volume change. Clearly in such cases space considerations preclude the possibility that a granite magma had been responsible for granitizing the pre-existing rocks.

Detailed examination of the relations between complex networks of granitic veins and structures in the invaded rocks frequently demonstrated their development by a replacement, rather than a dilation-injection mechanism.

P. E. ESKOLA, in reply to Professor Tilley and to Dr. King, said that granitization in connection with orogenesis involved a very considerable increase of volume, diapiric doming and intrusion. Cases of granitization at constant volume were not known to him, but if it occurred, it might be as well accounted for by magmatic metasomatism as by any other kind of metasomatism. In general, the space problem was not by any means easier to account for from the hypothesis of metasomatism in the solid state, as the atoms required their space anyway.

M. E. ROUBAULT also spoke, saying that it was quite certain that there were metasomatic granites, and that the question that now arose was whether magmatic granites really existed or not.

# THE ORIGIN OF THE SÖRMLAND GNEISSES

By NILS H. MAGNUSSON

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## ABSTRACT

The veined gneisses of Sörmland in Central Sweden are more or less strongly altered leptites, slates and granites and we must assume a long and complicated history of the Sörmland region preceding the metamorphism to veined gneisses. This alteration was caused by granitic emanations and solutions coming from deeper zones of the earth crust, where the paligenetic processes were stronger. Microscopical investigations and comparative studies of analyses from the region have shown that both the slates and the leptites, and even the old granites, have been altered in such a way that enrichment of the stablest constituents and impoverishment of the most soluble substances have taken place. We find a decrease of silica, alkalis and calcium and an increase of aluminium, iron and magnesium. In my opinion it is necessary to assume that granitic emanations and solutions soaked their way through the strongly schistose leptite-slate-granite complex, with its iron ores and limestones. In the roof of the veined gneisses the solutions have given rise to cross-cutting pegmatites and granites of the Fellingsbro- and Stockholm-types and to metasomatically formed mica-schists.

IN the province of Sörmland, in Central Sweden, veined gneisses are the predominant rocks. The present author has had opportunity of studying these rocks in connection with investigations of the iron ores of the Kantorp, Stav and Askö mines in the Western part of Sörmland and during a great many excursions in other parts of Sörmland and the neighbouring provinces.

As in other parts of the iron ore-bearing region in Central Sweden the iron ores of the Kantorp district belong to the leptite formation: the oldest, supercrustal, "Svionian" formation we know from the Swedish Archæan. This formation consists in its lower part of volcanic rocks, lava flows and dominating tuffs essentially of rhyolitic or keratophyric composition, with subordinate rocks of dacitic and andesitic composition. In Sweden these rocks are known as leptites and, where the rocks have dense groundmasses and are well preserved, as hälleflintas. The leptites are thus more or less metamorphosed hälleflintas.

The upper part of the leptite formation consists of true sediments, such as slates, greywackes, quartzites and conglomerates. These sediments belong, as we now know, to two different series, the Grythytte series and the Mälarsbo series, of which the latter seems to be somewhat younger than the former.

The sediments of the Grythytte series were probably deposited in local basins during quiet conditions, grey and black slates being the dominating rocks. The sediments of the Mälarsbo series on the contrary show rapid fluctuations between coarse-grained and fine-grained rocks, and original sandstones, usually rich in feldspar, with more or less clay-material are here the dominating types. These sediments must have been deposited in and around an area of strong relief.

In the province of Sörmland and around Lake Mälaren the rocks of the Mälarsbo series are widely developed, surrounded on all sides by the volcanic rocks of the leptite formation. The Mälarsbo series in this region builds up a complex synclinorium, with the underlying leptites projecting as lobes into the synclinorium or appearing as lens-shaped areas in the inner part of the Mälarsbo series.

Limestones appear both in the Mälarsbo series and in the subjacent leptite complex: sedimentary iron ores only in the leptites.

The first regional metamorphism took place in connection with an intense folding of the originally horizontal layers and in connection with the intrusion of the old Archæan granites that the Swedish geologists call "urgranites," the main mass of which was intruded during the folding. As a result of



the folding most of the rocks of the supercrustal formation and large parts of the "urgranites" received a more or less marked schistosity. The "urgranites" appeared in large masses and caused recrystallization of the supercrustal rocks and often also gave rise to new mineral associations in them. The normal leptites now got their granoblastic structure while the slates with sericite and chlorite were altered to crystalline schists with such high-temperature minerals as biotite, cordierite, garnet and andalusite. The limestones were altered to crystalline limestones, in England usually called marbles; and the quartz-banded hematite-ores were recrystallized and often partially or totally altered to magnetite ores. The banding has often disappeared in connection with the folding and the intrusion of the "urgranites." Where limestone or dolomite material had been deposited together with the quartz-banded iron ores, skarn-minerals, such as andradite, pyroxene and actinolite, resulted and all transitions exist between pure quartz-banded iron ores and skarn-ores with irregular magnetite concentrations in the skarn-masses.

By the action of solutions driven before the "urgranite"-front both skarn iron ores and quartz-banded iron ores are here and there partially or totally metasomatically altered to iron ores rich in MgO, with such minerals as anthophyllite, talc, forsterite, diopside, tremolite and so on. The surrounding leptites are contemporaneously altered to quartzites or mica-schists with such minerals as cordierite, andalusite, almandite and gedrite. This is the metasomatic alteration, usually known as magnesia-metasomatism, which has given rise to the sulphide ores of the Falun type. Often the above-mentioned metasomatic alteration to quartzites and mica-schists has regional extension, as for instance in the Riddarhytte field.

The folded leptite formation, the rocks altered by magnesia-metasomatism and the "urgranites" are older than the greenstone dikes, the metadiabases, which intersect them all in great number.

All the rocks and alteration processes named above are older than the transformation of the rocks of Central Sörmland into veined gneisses. Even the greenstone dikes, intersecting the "urgranites," have been altered together with the surrounding rocks. We must therefore assume a long and complicated history preceding this metamorphism, in essential features the same as in the central parts of the ore-bearing region of Central Sweden.

The alteration of the rocks to veined gneisses must have been caused by a regional sinking, by means of which large parts of Central Sweden were lowered into the deep earth zones, where palaeogenetic processes were predominant. This sinking was caused either by orogenic or by epeirogenic movements. I think epeirogenic movements to be more probable. We have not found in the non-gneissic region surrounding the area of the veined gneisses such tectonic features as would be expected if the sinking had been caused by an intense folding. What we can state is that the parallel structures are always very steep (80°–90°) except in the curvings of the layers, where the axes usually dip slightly (20°–30°). The steep dips of the parallel structures were caused by a strong tangential pressure but not by a new folding. I therefore think that the foldings are much older and that the strong pressure only caused a compression of the complex in one direction and a stretching out in another. The rock bodies existing before the alteration to veined gneisses were thus deformed and became more elongated.

The deformation was in some degree plastic as regards the details, but the detailed structures do not force us to assume more intense foldings of the whole complex of the veined gneisses.

The alteration to veined gneisses was caused by high temperature in connection with directed pressure and by emanations and solutions coming from deeper zones of the earth crust, where the palaeogenetic processes were stronger.

The veined gneisses are characterized by an inhomogeneous structure with coarser pegmatitic veins. Here and there appear small gneissic but homogeneous fragments of the original rocks which have escaped the stronger alteration. In the transition zones between the veined gneisses and the central part of the ore-bearing region, where normal leptites and sediments are the characteristic rocks, one can follow the alteration and see the pegmatitic parts develop as small spots or strings, which become more and more numerous. In the veined gneisses the pegmatitic veins dominate the rocks.



FIG. 1.—*Veined gneisses, cross-cutting pegmatites and Younger Svonian granites in Central Sweden.*

The whole mass of the rocks is usually recrystallized and pegmatitic. We can therefore also call the alteration process a pegmatitization. Among the homogeneous fragments in the veined gneisses we have leptytes, sediments (slates and feldspar-bearing sandstones), "urgranites," quartz-banded iron ores, skarn iron ores, and limestones. Among them the sediments and above all the slates seem to be most easily pegmatitized. Also the leptytes are much more easily altered than the "urgranites," which from the very beginning were relatively coarse-grained. Best preserved are the basic, granodioritic and quartz-dioritic intrusives. Among the leptytes the types rich in CaO are altered in a greater degree than those poor in CaO and the banded types in a greater degree than the more massive ones.

The alteration can be considered as a metamorphic differentiation. The most soluble or fusible constituents have been segregated in the form of more or less irregular spots and veins. That these spots and veins received pegmatitic structure depended upon the emanations and solutions that must have soaked through the whole complex from the beginning of the alteration process. We have excellent proof for this opinion in the chemical alterations that can be demonstrated. Microscopical investigations, and comparative studies of nineteen analyses from the Kantorp district in the Western part of Sörmland, have shown that both the sediments and the leptytes, and even the "urgranites,"



have been altered in such a way that an enrichment of the stablest constituents and an impoverishment of the most soluble substances have taken place. We find a decrease of  $\text{SiO}_2$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$  and even  $\text{CaO}$ , and an increase of  $(\text{Fe,Mg})\text{O}$ ,  $\text{Fe}_2\text{O}_3$  and  $\text{Al}_2\text{O}_3$ . As this alteration has also occurred in the slates, the increase of the last-named elements cannot be explained by a transport of material taken from the slates and the other sediments now available for our investigations. In my opinion it is necessary to assume that granitic emanations and solutions soaked their way through the strongly schistose leptite-sediment-granite complex with its iron ores and limestones.

The veins, which can be regarded as metamorphic differentiates from the rocks themselves, show all transitions to more independent, larger, pegmatites and, by way of these, to the younger granites of the region. The pegmatitic veins, sweated out from the rocks themselves, naturally vary according to the original chemical composition of those rocks. The larger pegmatite-masses are more independent of the composition of the surrounding rocks and are usually rich in quartz and microcline. The same tendency is still more pronounced in the younger granites, which often appear as central bodies in the pegmatitized areas. The granitic emanations and solutions causing the metasomatic alterations have always preceded the larger masses of pegmatites and these preceded the granites, with the appearance of which the alteration was finished. It is perhaps unnecessary to point out that it is a question of three stages of the same process, and that these stages follow each other and are intimately connected.

After the alteration process was essentially ended the pressure still continued and caused undulous extinction in the quartz grains of all the rocks of the region: the veined gneisses and the independent pegmatites as well as the younger granites. This gives us new proofs that the pegmatites and the granites originated during the alteration process that gave us the veined gneisses. The pegmatites and the younger granites are concentrated segregation products. The main mass has come from deeper parts of the earth crust. Partly, however, they may have come from the rocks now accessible for our investigations. It is consequently often difficult to determine whether we have larger segregations in situ or intrusions before us.

The mineral constituents of the veined gneisses are: quartz, plagioclase ( $\text{An}_{15} - \text{An}_{30}$ ), perthitic microcline and biotite in varying proportions, and together with these the characteristic  $\text{Al}_2\text{O}_3$ -rich minerals cordierite, almandite and sillimanite and, more rarely, andalusite. That such minerals should appear in the slates and the argillaceous sandstones is only natural; but they appear also in the leptites and the "urgranites," which rocks cannot normally give rise to them through metamorphism. In the slates and the sediments with slate-material graphite is rather general, especially in association with iron sulphides as sparse impregnations.

By the action of the wandering granite solutions and emanations the limestones have been altered to rocks rich in skarn-minerals which appear in veins, "schlieren" and irregular spots. The usual skarn-minerals are here diopside, tremolite, forsterite, spinel and serpentine.

The iron ores are more or less mixed with pegmatite material. In the Kantorp ores, for instance, all transitions appear between coarse-grained quartz-banded iron ores and even more coarse-grained ores consisting essentially of hæmatite, magnetite and feldspar. Quartz has been driven out and fixed in other parts of the deposit. In the skarn iron ores new skarn-minerals are mixed with the older ones forming a chaotic assemblage.

The author has come to the conclusion that the sediments of the Mälar series are the dominating rocks among the veined gneisses of supercrustal origin. N. Sundius on the contrary has recently expressed the opinions (1) that the veined gneisses of the Sörmland region have all originated from mafic leptites of volcanic origin; (2) that the  $\text{Al}_2\text{O}_3$ -rich minerals named above have come into existence through late-magmatic metasomatism, connected with the pegmatites; (3) that the pegmatites have come from the "urgranites"; and (4) that the pegmatites have no connection with the younger granites. Against these opinions it can be stated (1) that the "urgranites" outside the region of the veined gneisses, are never followed by pegmatites; (2) that the "urgranites" are altered in the same way but not so strongly as the supercrustal rocks; and (3) that there is an intimate connection between



the pegmatitic spots and veins of the veined gneisses and the more independent, more intrusive pegmatite masses, and that from these there are all transitions to the younger granites of the Stockholm-Fellingsbro types.

The connection with the younger granites referred to becomes clearer if we study the outer zone surrounding the central part of the Sörmland area on all sides. In this outer zone the pegmatites become more and more sharply bounded; they intersect the older rocks in all directions and the younger granites appear as more and more rounded massifs cutting the older structures, whereas the pegmatite and younger granite masses in the central zone have diffuse boundaries and are orientated parallel to the schistosity of the veined gneisses.

The cross-cutting pegmatites and granites in the outer zone must be considered as material that has passed through the central zone of the veined gneisses, loosening and assimilating material from these rocks. In the pegmatites of the outer zone we can often find such minerals as tourmaline, beryl, orthite and apatite, and in the iron ores cut by these pegmatites the same minerals also appear. The pegmatites are furthermore often followed by alterations of the leptites to mica-schists in which the same minerals are again enriched.

In the intrusion zone outside the central area of the veined gneisses there are also sulphide impregnations clearly connected with the pegmatites and the mica-schists. In this zone, south, south-west, and south-east of the central area pyrite, pyrite-pyrrhotite, pyrrhotite, copper pyrite-cobaltite, and sphalerite-galena occurrences are found. These occurrences must either be new formations in connection with the processes that gave us the veined gneisses, or older occurrences removed and strongly altered by these processes. In the central zone there exist no sulphide occurrences worth mentioning, only sparse impregnation. In the intrusion zone in the roof of the central area on the contrary the concentration to real occurrences could take place. The concentration occurred in the relatively well preserved parts of the very irregular—from the metamorphic point of view—outer zone. Often we can see a zoning of the sulphide minerals against local migmatite fronts. Finally the iron ores of this zone are usually more or less impregnated with varying sulphide minerals.

In the western parts of the ore-bearing region of Central Sweden, well preserved from the metamorphic point of view, there exist rounded or more irregular bodies of younger granites of the Stockholm-Fellingsbro types, granites rich in microcline and quartz and surrounded by pegmatites often in broad zones. There are all transitions between these granites and pegmatites and the granites and pegmatites in the outer zone of the area of the veined gneisses, and I am convinced that these intrusions appear in an upper zone in the roof of the veined gneisses or, in other words, that veined gneisses appear in the depth beneath these intrusions, which are to be considered as “diapires” above a metamorphic zone characterized by veined gneisses.

While the younger granites in the central part of the area of the veined gneisses are clearly gneissic and have very variable compositions, the granites outside this zone have more and more granitic structures and more and more homogeneous composition as we trace them from the inner, central zone outwards. The composition is approximately 70 to 75 per cent of feldspar and 20 to nearly 30 per cent of quartz and very small amounts of other minerals; the feldspar consists of microcline and plagioclase in approximately equal amounts. Through assimilation of older rocks, however, the composition is often more or less changed and variable. In this way granites rich in biotite or hornblende and with more calcic plagioclases have originated. Basic rocks (diorites and gabbros) connected with these granites are very subordinate and appear only in the uppermost zone.

The pegmatites following the uppermost granites have given rise to scheelite-molybdenite occurrences with subordinate sulphide minerals. Where the pegmatites have intruded limestones we find interesting occurrences with scheelite, molybdenite and sulphides in chaotic mixtures of pegmatite- and skarn-minerals, and remnants of limestone. In the iron ores the pegmatites have caused varying local alteration and have added new elements, such as Ti, W, Mo, Sn, Cu, P and so on.

According to Sundius the process that gave us the veined gneisses involved an addition of material,

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but he denies that a subtraction has also occurred. The facts presented above have been enough to convince at least the present author that the complex of the older rocks has acted as a "filter" holding back some elements and being permeable to others that could collect in different levels in the roof of the veined gneisses.

The solutions coming from the real paligenetic source beneath the zone of the veined gneisses must have had a granitic composition from the beginning.

### DISCUSSION

J. S. WEBB said he would be interested to hear Professor Magnusson's views regarding the mechanism or mechanisms whereby the metasomatizing emanations traversed the country rocks. Did his experience lend particular support in favour of any particular mode of transport, for instance by percolating hydrothermal solutions, or by the solid diffusion of ions?

N. H. MAGNUSSON : Both.

# THE TRANSFORMATION OF CALEDONIAN GRANODIORITE TO TERTIARY GRANOPHYRE ON SLIEVE GULLION, CO. ARMAGH, N. IRELAND

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## ABSTRACT

The rocks of the Slieve Gullion area, regarded as a whole, represent the deeply denuded relics of a Tertiary volcano that was in general form closely comparable to the modern volcano of Niuafoou Island, in the south-west Pacific. Like Niuafoou it had a caldera occupied by a lake, with an arcuate line of vents outside the caldera rim. The site of the caldera is now outlined by a ring-dike, composed of granophyre and to a lesser extent of felsite, which has been made familiar by Dr. Richey. Within the caldera pillow-lavas were erupted, followed by explosion breccias composed of Caledonian granodiorite, this volcanic pile being subsequently injected by many thick dolerite sills. Relics of these rocks are now preserved on Slieve Gullion, which rises from the centre of the area enclosed by the ring-dike.

The purpose of this communication is to describe a spectacular sequence of changes whereby Caledonian granodiorite, associated with this Tertiary volcano, has been converted to typical Tertiary granophyre. The initial stages of transformation appear within the solid granodiorite as the volcanic pile of Slieve Gullion, now downfaulted into the main conduit within the caldera, is approached. More advanced stages of transformation are found within layers of explosion breccia that form definite horizons on Slieve Gullion.

The details of the transformation are traced both as they appear in the field and under the microscope, and the perfection of the transition is illustrated by nine chemical analyses which when plotted form a regular variation diagram extending from Caledonian granodiorite to Tertiary granophyre.

## I. GEOLOGICAL SETTING

THE Slieve Gullion area, as is already well known from Dr. Richey's work (1932), is characterized by a spectacular ring-dike composed of granophyre and to a lesser extent of felsite. This ring-dike, which forms a well-marked circle of hills, conforms in a remarkable manner with the margin of the western end of the Newry complex, the country-rock enclosed by the ring structure thus being granodiorite of Caledonian age. Associated with the outer side of the south-western felsitic portion of the ring-dike is an arcuate line of vents filled with explosion breccias, tuffs, and basaltic and trachytic lavas. The explosion breccias are composed mainly of rounded blocks of Caledonian granodiorite, or of smaller fragments of the granodiorite embedded in a matrix of finely comminuted material.

Within the ring-structure rocks of Tertiary age form the eminence of Slieve Gullion and two smaller hills to the south-east near Flurrybridge. The hills carved from these Tertiary rocks rise from flat, low-lying and not uncommonly marshy country formed by the Caledonian granodiorite. Slieve Gullion, which rises steeply to a height of 1,894 feet from about the middle of the area, has a distinct terraced topography on its western side.

Before the present investigation was begun two years ago the Tertiary rocks within the area enclosed by the ring-dike were regarded as plutonic intrusions of gabbro, granophyre and intermediate rock varieties. This recent work, however, has revealed the fact that the rocks of Slieve Gullion are in reality the much altered relics of a Tertiary volcanic pile that has been downfaulted and neatly inset into the Caledonian granodiorite. Slieve Gullion is built of a pile of gently dipping layers of rock. At its base are layers of basaltic rocks including pillow-lavas, and at higher levels there are layers of transformed Caledonian granodiorite. On account of their position above Tertiary lavas, the latter can only be interpreted as explosion breccias allied to those within the vents outside the ring-dike.



There are also thick layers of granophyre and of aplitic granophyre at higher levels. Into this volcanic pile many dolerite (some gabbro) sills have been intruded, so that the hill is built largely of an assemblage of gently dipping layers of volcanic rocks and sills cut through by a swarm of younger dolerite dikes. The two smaller hills near Flurrybridge are separated from Slieve Gullion by a major fault that bisects the ring-dike and has a large westerly throw. The more westerly of these hills has a layered structure reminiscent of Slieve Gullion. The more easterly is a vent filled with great masses of basaltic and doleritic rocks, granophyre and Caledonian granodiorite.

The rocks of the Slieve Gullion area, regarded as a whole, represent the deeply denuded relics of a Tertiary volcano that was closely comparable, in general form, to the modern volcano of Niuafou Island in the south-west Pacific (Jaggar, 1931). Like Niuafou the Slieve Gullion volcano had a caldera (now outlined by the ring-dike) occupied by a lake, as is evidenced by the presence of pillow-lavas; and, as on Niuafou, the Slieve Gullion volcano had an arcuate line of vents outside the caldera rim from which basalts and explosion breccias were erupted. The rocks of the three Tertiary areas within the ring-dike occupy the sites of what were once the main conduits of the volcano.

A full description of the area, which is being mapped on the six-inch scale, must be deferred to a future date. The purpose of the present communication is to describe a spectacular sequence of changes whereby the Caledonian granodiorite associated with this Tertiary volcano has been converted to Tertiary granophyre. The initial stages of alteration appear within the solid granodiorite which forms the sunken mass that floored the caldera and is now enclosed by the ring-dike. The change appears both as Slieve Gullion and as the more easterly of the hills near Flurrybridge are approached.\* Further stages of alteration are exhibited by a gigantic block of granodiorite within the vent exposed on the more easterly of the hills near Flurrybridge. More marked changes still, culminating in a complete transformation to granophyre, characterize the granodiorite of the explosion breccias on Slieve Gullion itself.

Granitization of geosynclinal rocks in an orogenic setting has received much attention in recent years, but the example of granitization that is here described is at present almost unique in that it has a kratogenic setting. The most marked transformation took place within rocks that formed part of the superstructure of a volcano, so that there can be no doubt that it was performed at a high level in the earth's crust. The primary cause of the migrations of material that brought about the transformation of Caledonian granodiorite to Tertiary granophyre can hardly be other than volcanic heat transported to high levels through the agency of basaltic magma. Basaltic magma flowing upwards through the main conduits of the volcano was responsible for the changes now seen in the solid granodiorite as the hills of Slieve Gullion and Flurrybridge are approached. It was the combined heat of many dolerite sills injected into the volcanic pile, however, that brought about the complete transformation of granodiorite to granophyre within the layers of explosion breccia on Slieve Gullion.

## II. THE TRANSFORMATION OF CALEDONIAN GRANODIORITE ADJOINING THE TERTIARY ROCKS WITHIN THE RING-DIKE

(a) *Varieties of Granodiorite.*—Within the area enclosed by the Tertiary ring-dike two varieties of Caledonian granodiorite are represented, the distribution of which has already been mapped (Reynolds, 1944, Fig. 1, p. 209). One of these varieties is a little more basic than the other and in it hornblende is almost if not quite as abundant as biotite. This variety, as in previous publications, will be referred to as hornblende-granodiorite. In the other variety hornblende is only sparsely present, and may be absent; conformably with earlier descriptions this variety will here be termed biotite-granodiorite.

On the western, *i.e.*, the Slieve Gullion, side of the Camlough fault—a major fault that bisects the area—hornblende-granodiorite only is represented. On the eastern, *i.e.*, the Flurrybridge, side of the fault both varieties of granodiorite are present within the area enclosed by the ring-dike, but at the one locality where granodiorite is exposed in close proximity to the Tertiary rocks of the Flurrybridge area it is the biotite-granodiorite that is concerned.

\* No exposures of granophyre have yet been found near the more westerly of the Flurrybridge hills.

Since both varieties of granodiorite have already been described in detail (Reynolds, 1944) it will be sufficient here to summarize some of their relevant characteristics. In both varieties plagioclase, with the bulk composition of oligoclase, is considerably more abundant than potash feldspar, and tends to be euhedral. The plagioclase commonly exhibits zoning of an oscillatory type in which zones of andesine and oligoclase, with large optic axial angles, alternate; the outer zone never departs far from  $An_{15}$ .

In the hornblende-granodiorite potash feldspar is present in small amount only, and occurs interstitially. It is slightly perthitic and commonly shows a patchy extinction; rarely it exhibits the distinctive cross-hatch twinning of microcline. In the biotite-granodiorite the potash feldspar, perthitic microcline, forms large anhedral individuals enclosing plagioclase and biotite in poikilitic fashion. In both varieties the quartz occurs in glomerogranular groups; the hornblende is a common green variety; and the biotite, which is pleochroic from dull greenish brown to straw colour, is sometimes partially or entirely altered to chlorite. The accessory minerals are sphene, iron-ore, apatite, zircon and allanite.

(b) *Caledonian Granodiorite adjoining the Tertiary rocks of Slieve Gullion.*—Where the Caledonian granodiorite is exposed in proximity to the Tertiary rocks of Slieve Gullion, and to the more easterly of the two hills near Flurrybridge, it shows marked signs of alteration. It loses its bright lustre, and assumes a brownish tint that contrasts strongly with its normal glistening white colour. To the north and west of Slieve Gullion, where the granodiorite is relatively well exposed, this alteration extends to a distance of 900 feet or more from the contacts with the Tertiary rocks.

Microscopically the gradual transformation of the hornblende-granodiorite, as Slieve Gullion is approached, is highly spectacular. The first signs of change are shown by the hornblende and biotite which become speckled with or outlined by iron-ore. Towards the contacts with the Tertiary rocks this alteration becomes more and more marked, and finally the sphene also becomes rimmed with black iron-ore. At the same time the colour of the biotite changes from its normal dull greenish brown to the reddish colour characteristic of hornfelsic biotite. The hornblende shows an even more marked change, for it gradually becomes pseudomorphed by aggregates of small granules of a very pale coloured monoclinic pyroxene. The nature of these changes suggests that they were effected in response to rising temperature, and that the adjustments necessitated an excretion of iron oxide from both biotite and hornblende.

Concomitantly with the progressive alteration of the hornblende and biotite, parallel-sided zones of potash feldspar, with a brown pigmentation, appear along the contacts between plagioclase and quartz so that in section each quartz group is outlined by a brownish rim. At a distance of about 900 feet from the Tertiary rocks these rims are exceedingly narrow, in fact so narrow that they could easily be overlooked. As the contact is approached, however, they progressively broaden until they are about 0.07mm. wide, when they present a very striking appearance (Plate I, Fig. 1). In any particular rock specimen the potash feldspar rims maintain an approximately uniform width. Although these rims margin the quartz groups they are actually formed at the expense of neighbouring oligoclase crystals. This is seen by inserting a gypsum plate and viewing the sections between crossed nicols. Each rim is formed of several individuals of orthoclase, and each individual conforms in extent and optical orientation with a neighbouring oligoclase crystal. Where potash feldspar adjoined the quartz groups within the initial rock it is now pigmented like the potash feldspar of the rims.

Close to the contact with the Tertiary rocks fingering processes of potash feldspar extend from the rims into the quartz groups. Sometimes these fingering processes advance along the boundaries between quartz grains, but more commonly they actually penetrate into individual quartz grains. In the latter case there can be no doubt that quartz has been replaced by potash feldspar.

Granodiorite showing an advanced stage of development of the potash feldspar rims is well exposed on the western side of Camlough reservoir, a few yards north of the Tertiary granophyre that margins the northern end of Slieve Gullion. The actual contact is not exposed. In the rock from this locality potash feldspar rims with fingering projections into the quartz groups are well developed, and the



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mafic minerals are also highly altered. The hornblende is largely replaced by pyroxene granules and iron-ore, and the biotite, which is speckled with iron-ore, has a reddish colour. The biotite, moreover, has either acquired a spongy texture, or has recrystallized as aggregates of flakes. Iron-ore is also associated with the sphene.

The chemical analysis and norm of a typical specimen of this rock is recorded under 2 in Table I, and the chemical analysis and norm of a typical specimen of the hornblende-granodiorite of which it is the alteration product is recorded under 1 in Table I for comparison. Chemically the transformed

TABLE I

## Chemical Analyses

	1	2	3	4	5
SiO <sub>2</sub>	63.22	65.68	64.92	66.93	
Al <sub>2</sub> O <sub>3</sub>	15.94	16.06	17.13	16.38	
Fe <sub>2</sub> O <sub>3</sub>	1.71	1.43	0.86	1.07	
FeO	2.56	2.62	3.15	2.36	
MgO	2.87	2.22	2.16	1.88	
CaO	4.19	3.58	2.32	3.02	
Na <sub>2</sub> O	3.88	3.86	4.04	4.02	4.12
K <sub>2</sub> O	2.89	3.10	3.40	2.87	3.02
H <sub>2</sub> O+	1.04	0.34	0.67	0.60	
H <sub>2</sub> O—	0.38	0.09	0.18	0.14	
CO <sub>2</sub>	trace	none	none	none	
TiO <sub>2</sub>	0.88	0.57	0.72	0.59	
P <sub>2</sub> O <sub>5</sub>	0.29	0.31	0.26	0.24	
MnO	0.04	0.03	0.08	0.04	
	99.89	99.89	99.89	100.14	

## Normative Compositions

	1	2	3	4
Q	16.57	20.03	19.11	22.80
or	17.08	18.31	20.09	16.98
ab	32.82	32.66	34.18	34.03
an	17.55	15.72	9.84	13.38
C	none	0.59	3.19	1.74
di { CaSiO <sub>3</sub>	0.58	—	—	—
MgSiO <sub>3</sub>	0.41	—	—	—
FeSiO <sub>3</sub>	0.12	—	—	—
hy { MgSiO <sub>3</sub>	6.74	5.53	5.38	4.68
FeSiO <sub>3</sub>	1.79	2.74	4.04	2.56
mt	2.48	2.08	1.25	1.55
il	1.67	1.08	1.37	1.12
ap	0.67	0.74	0.59	0.57
water	1.42	0.43	0.85	0.74
	99.90	99.91	99.89	100.15

1. Hornblende-granodiorite (1726). About 1,100 yards north-east of Cashel Bridge. Analyst, W. H. Herdsman.
2. Hornblende-granodiorite (192), slightly transformed. Western bank of Camlough reservoir, a few yards north of the granophyre that margins the northern end of Slieve Gullion. Analyst, W. H. Herdsman.
3. Micrographic granodiorite (73B). Upper horizon of transformed granodiorite, north-western side of Slieve Gullion. Analyst, W. H. Herdsman.
4. Micrographic granodiorite (4697). Upper horizon of transformed granodiorite, western side of Slieve Gullion.
5. Micrographic granodiorite (1541). Upper horizon of transformed granodiorite. South-western flank of Slieve Gullion, close to the end of the path from Drumintee. Analyst, W. H. Herdsman.

granodiorite is closely similar to the initial hornblende-granodiorite. It has a slightly higher  $K_2O/Na_2O$  ratio, and slightly higher total alkalis and silica than the hornblende-granodiorite, and the sum of total iron,  $MgO$  and  $CaO$  is a little lower. These differences are so slight that in themselves they could hardly be regarded as more than the normal variation that might be expected to obtain between any two specimens of the same rock. It will be shown, however, by reference to further examples, that increase in the  $K_2O/Na_2O$  ratio and/or in the percentage of total alkalis, with a concomitant increase in silica, and a gradual decrease in the feldspar constituents, is a persistent feature in the transformation of the granodiorite. Both from microscopic and chemical evidence it can therefore be accepted with confidence that the development of the rims of potash feldspar around the quartz groups, together with the alteration of the biotite and hornblende, represent not only a reconstitution of the original Caledonian granodiorite, but form the first link in a continuous chain of mineralogical and textural changes, involving introduction and fixation of  $K$  and  $Si$ , and displacement and removal of  $Fe$ ,  $Ca$ , and  $Mg$ . If at this stage additional supporting evidence be required to show that the small increase in the  $K_2O/Na_2O$  ratio of the transformed granodiorite is of significance, then comparison can be made with the  $K_2O/Na_2O$  ratios of seven analyzed specimens of Caledonian granodiorite from the western end of the Newry complex (Reynolds, 1937, p. 258; 1941, p. 16; 1944, p. 212). Whereas the  $K_2O/Na_2O$  ratio of the transformed granodiorite in question is 0.80, the  $K_2O/Na_2O$  ratios for the seven analyzed specimens of normal granodiorite are: 0.76, 0.74, 0.74, 0.72, 0.68, 0.67, 0.54. Since the  $K_2O/Na_2O$  ratio for the transformed granodiorite is higher, and the percentage of  $K_2O$  is greater than in any of the seven analyzed specimens of typical granodiorite, it can fairly be concluded that the alteration involved a slight increase of  $K_2O$ . The amount of potash feldspar in the rims, however, appears to be greater than can be accounted for by a 0.2 per cent increase of  $K_2O$ , and its growth probably depended in part on a supply of potassium liberated by the destruction of biotite.

(c) *Caledonian Granodiorite adjoining the Flurrybridge vent.*—As the vent exposed on the more easterly of the Flurrybridge hills is approached the Caledonian granodiorite (biotite-granodiorite) becomes altered in exactly the same way as it does in the vicinity of Slieve Gullion. Here, however, the rims reach a slightly greater width, measuring about 1 mm. or a little more in breadth close to the contact (Plate I, Fig. 2). Every rim is composed of several units of potash feldspar, each conforming in extent and optical orientation with an adjoining crystal of plagioclase. This evidence, as in the previous example, indicates that the rims have been formed at the expense of plagioclase. Further evidence is found in some cases where small patches of plagioclase, in optical continuity with the marginal part of an adjoining plagioclase crystal, remain as isolated relics within the feldspar rim.

### III. FURTHER STAGES OF TRANSFORMATION OF CALEDONIAN GRANODIORITE WITHIN THE FLURRYBRIDGE VENT

A more advanced stage of transformation characterizes the biotite-granodiorite which occurs as a gigantic block within the Flurrybridge vent. Although the granodiorite of the greater part of the exposed portion of the block is markedly transformed, a specimen collected 45 feet from its southern margin is remarkably little changed. The rock of this specimen is composed of glomerogranular groups of quartz; oligoclase and microcline, of which the former predominates; dull brown biotite partly altered to chlorite; epidote, and accessory apatite and iron-ore. The microcline encloses small crystals of oligoclase.

As the southern edge of the block, which adjoins a doleritic rock of Tertiary age, is approached, the granodiorite shows a marked change; it loses its bright lustre, and distinct brownish rims appear around the quartz groups. In microscope sections of a specimen collected about 30 feet from the edge of the block this change is highly spectacular. Every glomerogranular group of quartz is rimmed by a zone of micropegmatite about 0.4 mm. wide, and each rim is remarkably uniform in width (Plate I, Fig. 3). The micropegmatite has resulted from the partial replacement of the peripheral zones of the quartz groups by potash feldspar. This is evidenced by the fact that the quartz of the micropegmatite sometimes still remains optically continuous with the adjoining quartz of the enclosed group, although



this is by no means always so, the quartz having commonly recrystallized. It is further evidenced by the presence of fingering processes of potash feldspar that extend from the inner side of the rims into the central quartz groups. These fingering processes of potash feldspar extend for a short distance into the quartz and then divide and follow rhombohedral planes. In this way narrow lanes of potash feldspar sometimes ramify through the central quartz groups, surrounding and isolating diamond-shaped sections of quartz, and thus transforming the quartz to micropegmatite.

Within the transformed rock the microcline of the initial granodiorite is represented by untwinned potash feldspar which, like the microcline of the original rock, encloses small crystals of oligoclase. The feldspathic portions of the initial granodiorite, however, and more particularly the large oligoclase crystals, are now in part represented by confused aggregates of small plagioclase crystals, sometimes intricately intergrown with potash feldspar and/or quartz. The dull brown biotite of the initial granodiorite is represented within the transformed rock by compact or scattered aggregates of small orange-tinted flakes associated with black iron-ore.

The alkalis of the least altered biotite-granodiorite collected 45 feet from the edge of the block, and of its transformed facies collected 30 feet from its edge, have been determined by W. H. Herdsman, and these together with the  $K_2O/Na_2O$  ratios are as follows:—

	<i>Least altered granodiorite from block</i>		<i>Transformed granodiorite from block</i>
$K_2O$ .....	2.95	.....	3.82
$Na_2O$ .....	4.09	.....	3.90
$K_2O/Na_2O$ .....	0.72	.....	0.98

Both the  $K_2O$  and the  $K_2O/Na_2O$  ratios are considerably higher in the transformed marginal facies than in the less altered granodiorite further within the block; they are also considerably higher than those of the transformed granodiorite from the northern end of Slieve Gullion (Table 1, No. 2, p. 23).

#### IV. THE TRANSFORMATION OF CALEDONIAN GRANODIORITE TO GRANOPHYRE AT TWO HORIZONS ON SLIEVE GULLION

Two horizons composed largely of Caledonian granodiorite (hornblende-granodiorite) occur within the volcanic pile of Slieve Gullion. The lower of these is about 20 feet thick, and the upper about 100 feet. Since these horizons overlie Tertiary pillow-lavas they can be interpreted only as explosion breccias of Tertiary age composed of blocks of Caledonian granodiorite that have become welded together, the breccias as a whole having acquired a rectangular jointing so that they now resemble the solid granodiorite. This is a not unusual feature of the explosion breccias within the small vents outside the ring-dike, but in these occurrences the outlines of the original blocks are still discernible.

The granodiorite of the two horizons on Slieve Gullion is associated with finer grained granophyric rocks of Tertiary facies. Two of the latter types—micrographic adamellite and micrographic microgranite—form the end stages of transformation of the Caledonian granodiorite. In order to keep this communication within the prescribed limit of length, however, consideration of these fine-grained rocks is left for a future paper.

The Caledonian granodiorite of the two horizons on Slieve Gullion has an abnormally dull lustre, and on close inspection it appears as if its glomerogranular quartz groups and large plagioclase crystals were set in a sparse brownish matrix. In thin sections the granodiorite presents very varied appearances of which only those that directly concern the subject matter of this paper need be described here. The variability in thin sections is in the main dependent on the degree of transformation towards or to granophyre undergone by the initial rock, and this varies from place to place. It should be stressed, however, that the various stages of change are only recognizable in microscope sections. Macroscopically the rock has a very uniform appearance because the granophyre end-product of the transformation actually pseudomorphs the Caledonian granodiorite.

The least transformed rock is illustrated by the thin section shown in Plate I, Fig. 4. The quartz

groups of the original granodiorite are here surrounded by broad rims of micropegmatite about 0.5 to 0.8 mm. wide. These rims are commonly composed of two varieties of micropegmatite. One of these, resembling that already described from the Flurrybridge example, consists of diamond-shaped or irregular quartz individuals in association with roughly rectangular forms of potash feldspar. The quartz and feldspar of this implicate texture are of equal importance and size, neither acting as host to the other. This variety of micropegmatite adjoins the glomerogranular quartz groups from which, as in the Flurrybridge example, it can be seen to have developed. The other variety of micropegmatite occurs in the peripheral part of the rims, away from the central quartz groups. In it potash feldspar forms the host within which quartz either ramifies in a lace-like pattern or appears as parallel streaks; in both cases considerable areas of quartz are optically continuous. The host feldspars of this lace-like micropegmatite have been formed by replacement of the marginal part of the plagioclase crystals that originally adjoined the glomerogranular groups of quartz. The quartz that is now intergrown with the potash feldspar in micropegmatitic fashion is evidently "quartz de corrosion."

By comparison with the less transformed granodiorite of the Slieve Gullion and Flurrybridge areas described in the preceding pages, the origin of the rims composed of two varieties of micropegmatite can be deciphered. It will be recalled that in the initial stages of rim development potash feldspar was formed by replacement of the marginal parts of plagioclase crystals where they adjoined quartz. In more advanced stages of alteration micropegmatite was then evolved, on the inner side of this initial rim of potash feldspar, by replacement of the central quartz groups. This would liberate silicon, and it seems very probable that it is this excess silicon that has invaded the potash feldspar of the outer rim and given rise to the fine-grained, regular, lace-like micropegmatite. Both the inner and outer micropegmatite zones are considerably broader than the corresponding micropegmatite and potash feldspar zones of the initial stages of transformation. In consequence the residual parts of the glomerogranular quartz groups are now much smaller in size, as a result of the encroachment upon them of the inner zone of micropegmatite. Similarly, the plagioclase crystals adjoining the outer margins of the zones of lace-like micropegmatite have become rounded in form and diminished in size with progressive replacement by the lace-like micropegmatite.

For ease of presentation the composite rims have here been described as though they always show a perfect development, with a complete inner zone of relatively coarse and somewhat irregular micropegmatite, and a complete outer zone of relatively fine lace-like micropegmatite. This, however, is by no means always the case. The outer zone of lace-like micropegmatite is commonly quite patchy in its development, forming an interrupted rim which sometimes branches out along the sides of neighbouring plagioclase crystals. In other examples the inner zone of somewhat crude micropegmatite is sometimes absent, its development appearing to have been inhibited by the growth of crystals of pyroxene along the margin of the quartz groups (Reynolds, 1937, Plate 22, Fig. 2). In spite of these variations, an examination of the rims around the residual quartz groups in many thin sections leaves no doubt that the general arrangement is one in which there is an inner zone of the crude micropegmatite developed at the expense of quartz, and an outer zone of lace-like micropegmatite evolved from plagioclase.

This is not the only way in which micropegmatite is formed from the original granodiorite. Large crystals of plagioclase that still retain their oscillatory zoning are sometimes ramified by "quartz de corrosion" and converted to a lace-like micropegmatite (Plate II, Fig. 7). Where such crystals occur close to the rims around the quartz groups the quartz in these micropegmatitic oligoclase crystals is commonly optically continuous with the quartz of adjoining lace-like micropegmatite in the outer part of the rim. Optically continuous quartz thus cuts across from micropegmatite in which potash feldspar is the host into micropegmatite in which plagioclase is the host.

Oscillatory zoned plagioclase is not only converted to micropegmatite; it is also commonly transformed to aggregates of small oligoclase crystals which are either unzoned, or exhibit an even zoning from a more calcic core to a more sodic rim. This transformation may affect the whole of the original crystal or be restricted to its core (Plate II, Fig. 8).



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The biotite of the initial granodiorite is now represented either by aggregates of small reddish flakes commonly speckled with granules of iron-ore, or by ghost-like relics from which all trace of the original biotite has vanished except the cloud of iron-ore granules. Both hornblende and pyroxene are present. The hornblende is residual from the initial granodiorite, whereas the pyroxene has been newly evolved in response to rising temperature. Hornblende is sometimes almost completely pseudomorphed by aggregates of pyroxene granules. More commonly, however, the hornblende has disappeared and is now represented by small prismatic crystals of pale green pyroxene. Monoclinic pyroxene is the most common representative of this group, but hypersthene is sometimes also present.

Where the granodiorite is even more strongly transformed the glomerogranular quartz groups of the initial rock have been completely replaced by the relatively coarse variety of micropegmatite. In thin section this micropegmatite now appears as discrete patches surrounded by more or less perfect rims of the relatively fine-grained lace-like micropegmatite (Plate II, Figs. 5, 6). Macroscopically the rock is still recognizable as Caledonian granodiorite, but microscopically it is now Tertiary granophyre. If homogenization of the end-product had been attained, or if the various stages in its evolution had been less well preserved, the granophyre might have been assumed to have crystallized from granitic magma. Faced with the clearly displayed evidence of replacement it is, of course, easy to recognize that the mineralogical and textural associations within this particular granophyre are irreconcilable with crystallization of magma of eutectic composition. There is then perhaps a danger of concluding that there may be granophyres *and* granophyres. It is therefore important to recall that the granophyres of the Red Hills of Skye have much in common with the rock here described. Of them Harker (1904, p. 161) wrote: "In different specimens, and in different parts of one specimen, the micropegmatite differs in composition, in scale of magnitude, and degree of regularity, in manner of arrangement and

relation to phenocrysts, etc. The component minerals are usually orthoclase and quartz: less commonly oligoclase takes the place of the former."

In Table I the chemical analyses of two specimens of transformed granodiorite from the explosion breccia on Slieve Gullion, and the alkali determinations for a third, are recorded. These analyses show the rock to be a little richer in silica and total alkalis than the initial hornblende-granodiorite, and to have lower contents of iron oxides, MgO and CaO. The chemical change is surprisingly small, however, considering the drastic way in which the rock has been reconstituted. It is still a granodiorite, and in order to distinguish it from other more acid and more potassic granophyric rocks on Slieve Gullion it will be termed micrographic granodiorite.

Text-fig. 1 shows graphically the fields of alkali ratios for the Caledonian granodiorite of the Newry Complex, the Tertiary acid rocks of Northern Ireland, and the various stages of transformed granodiorite in the Slieve Gullion area. From the diagram it is apparent that in their alkali ratios the Caledonian and Tertiary acid rocks are widely separated, the transformed rocks bridging the gap between them.

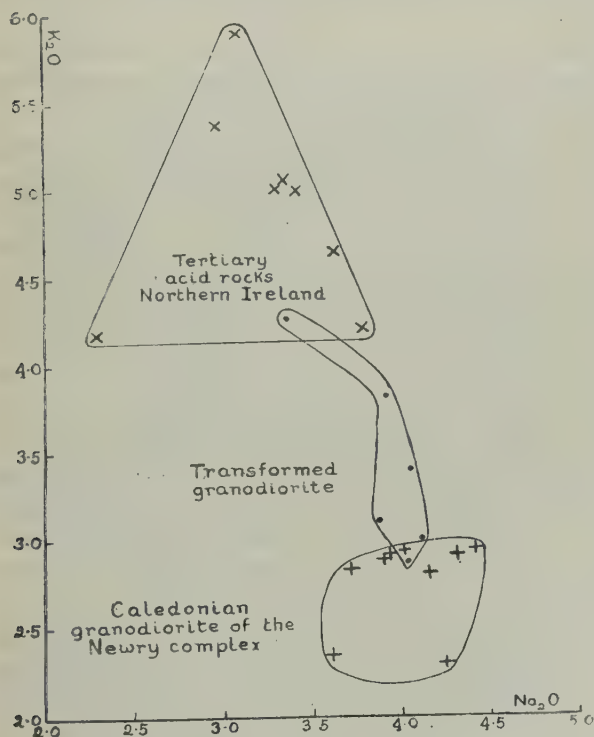


FIG. 1.

*K<sub>2</sub>O-Na<sub>2</sub>O diagram illustrating the transition from Caledonian granodiorite to Tertiary granophyre.*

### PART III: METASOMATIC PROCESSES IN METAMORPHISM

#### V. THE CAUSE OF THE TRANSFORMATION

Outside the ring-dike there are two small gabbro plugs that probably once fed surface flows. One of these is situated to the south-west, and the other to the north of the ring-dike. As has already been described by the writer (Reynolds, 1937, 1941) the Caledonian granodiorite adjacent to both these plugs is transformed in a manner comparable with that described in the present paper. As the gabbro plug to the north of Camlough Mt. is approached the glomerogranular quartz groups of the Caledonian granodiorite become rimmed by narrow zones, 0.1 mm. broad, of micropegmatite (1937, p. 259, and Plate 22, Fig. 3). The micropegmatite is fine in grain, but has an irregular texture like that which replaces quartz in the Slieve Gullion rocks. As on Slieve Gullion the evidence in the Camlough occurrence indicates that the micropegmatite has formed as a result of the partial replacement of the peripheral zones of the quartz groups by potash feldspar. The exposures around the gabbro plug of Camlough Mt. are not good, so that it is impossible to gain any idea as to distance from the plug to which the transformation penetrates. In the Mullaghbawn occurrence narrow rims of felsite (commonly spherulitic) appear around the quartz groups at a distance of 11 feet from the contact, and as the contact is approached they broaden until at a distance of 2 feet from the gabbro they are 0.34 mm. wide (Reynolds, 1941, Plate I, Figs. 2, 3, and 4). At the immediate contact the granodiorite is completely reconstituted and transformed to craignurite. The rimmed rock away from the contact has been enriched in potash which can, at any rate in part, be accounted for as K displaced from the rock at the immediate contact with the gabbro.

In the examples of rim development within the granodiorite adjoining the gabbro plugs of Mullaghbawn and Camlough there can be no doubt that the agent responsible for the transformations was basaltic magma now represented by the gabbro of the plugs. The gabbroic as distinct from a basaltic texture of the basic rocks provides some measure of the high temperature that was attained, and probably maintained for a considerable period.

Now whereas there is this definite evidence within the area that basaltic magma has implemented the transformations under discussion, it is important to notice that no such transformations are shown by the granodiorite adjoining the granophyre-felsite ring-dike either on its inner or outer sides. The ancestry of the acid rocks of the ring-dike has still to be investigated, but if it be assumed that the rocks were emplaced as magma then it must be concluded that acid magma was incapable of bringing about these transformations.

Within the area enclosed by the ring-dike the transformation of granodiorite adjoining and within the Flurrybridge vent can again be correlated within the flowage of basaltic magma up the conduit, whilst on Slieve Gullion the transformation of granodiorite to granophyre within layers of explosion breccia is attributable to the emplacement of thick dolerite sills. In the upper horizon of explosion breccia granodiorite is transformed to granophyre throughout a thickness of 100 feet. This horizon is margined both above and below by basic sills 100 and 200 feet thick respectively, the gabbroic texture of the upper of which again testifies to the attainment and maintenance of a high temperature.

In the light of the preceding evidence, the transformation of the granodiorite surrounding the almost horizontal piles of rock forming Slieve Gullion and the westerly hill near Flurrybridge is most satisfactorily explained by supposing that the layered rocks have been downfaulted into the main conduits of the volcano. The long-continued flow of basaltic magma up a wide conduit to the surface would account for the great breadth of the transformed zone—about 900 feet—around Slieve Gullion.

Consideration of the source of the potash necessary for the transformation and the destiny of the displaced Fe, Mg, and Ca is deferred until the investigation of the area is completed. It is perhaps not out of place, however, to make some comment here on the selective way in which the potash feldspar rims of the initial stage of change, and the micropegmatite in the more completely transformed granodiorite, are restricted to the boundaries of the quartz groups.

It has been demonstrated by Forsyth, King, Metcalfe, and Chalmers (1946) that the degree of growth of a second phase along the grain boundaries in single-phase alloys is correlatable with the



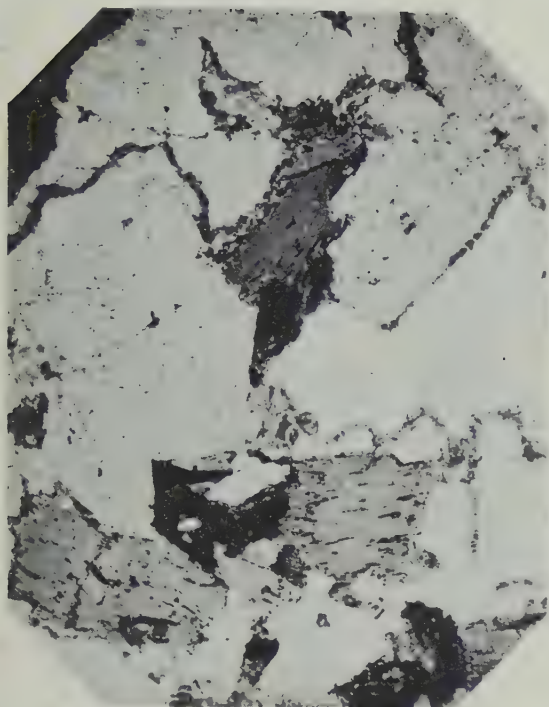


FIG. 1.

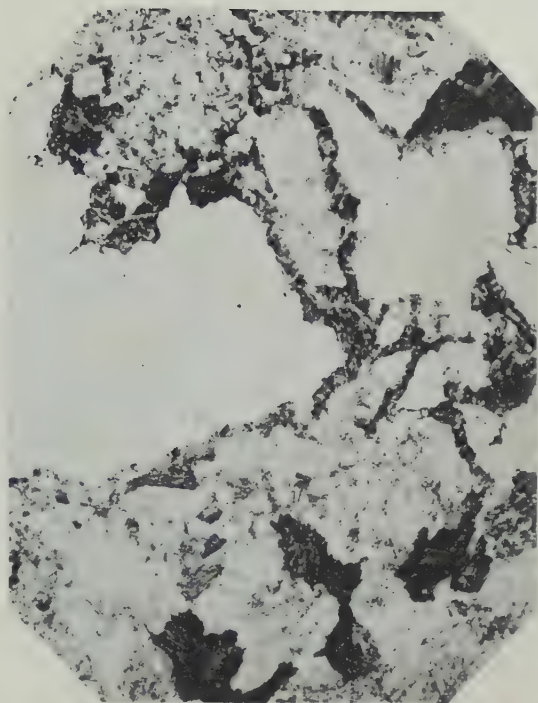


FIG. 2.



FIG. 3.

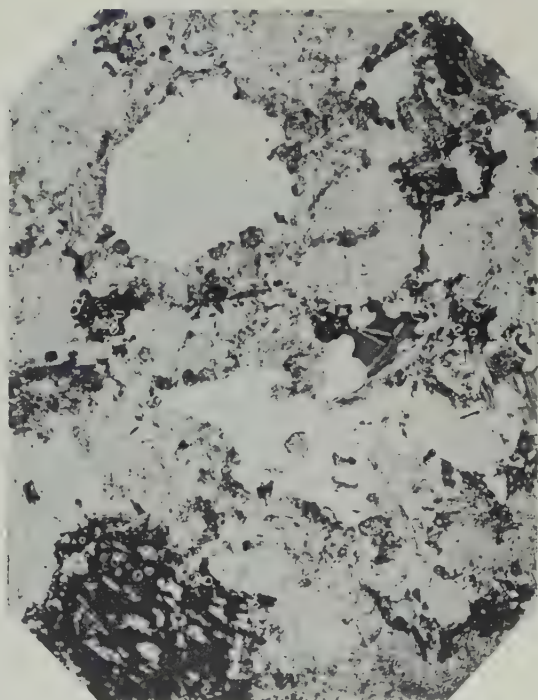


FIG. 4.



FIG. 5.

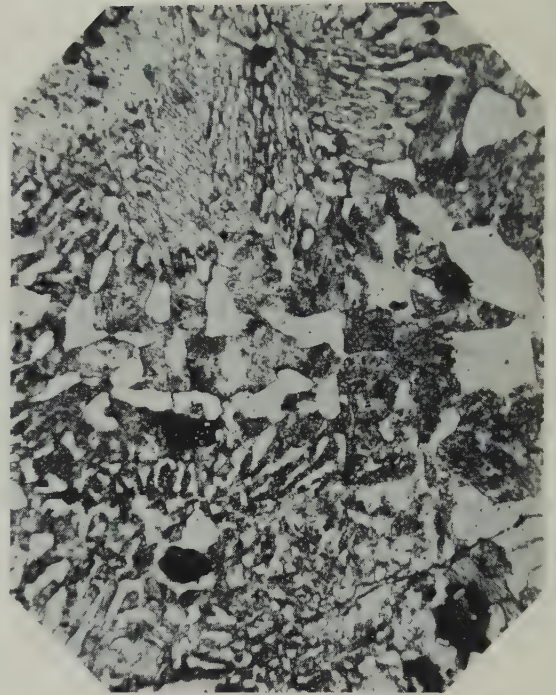


FIG. 6.

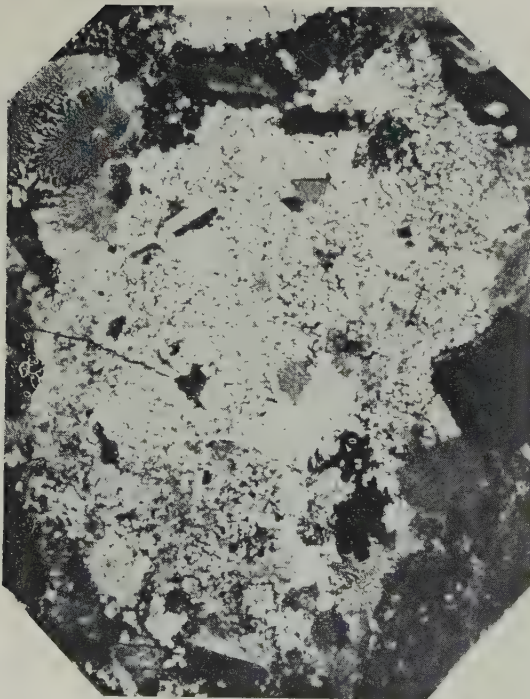


FIG. 7.

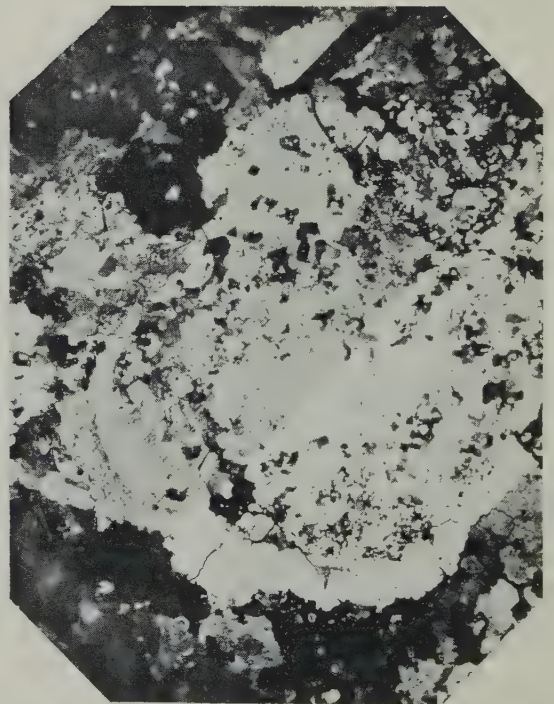


FIG. 8.



relative orientation of the crystals on either side of the boundary. Since it is reasonable to suppose that zones of atomic disorder, probably only a few atomic diameters in thickness, are present along crystal boundaries, and that the degree of this disorder will vary according to the relative orientation of the adjacent crystal lattices, the investigators concluded that the degree of growth of the second phase is dependent on such atomic disorders.

These conclusions appear to have a direct bearing on the rim-formation described in this paper, the more so because zones of atomic disorder provide pathways for migratory elements. In the initial stage of transformation of the granodiorite (Plate I, Fig. 1), whereas there is no discernible growth of potash feldspar between adjacent plagioclase crystals, there is conspicuous development of potash feldspar along the quartz-plagioclase boundaries, that is, where the degree of atomic disorder may reasonably be supposed to have been considerably greater. As narrow rims of potash feldspar grew by replacement of these zones, further atomic disorder would develop concurrently on either side of the newly formed potash feldspar. Once the rims began to grow, their very growth would thus promote conditions conducive to further broadening, given an adequate supply of migratory potash.

#### ACKNOWLEDGMENT

The results presented in this paper form part of a major study of the Tertiary rocks of the Slieve Gullion area that has been made with the aid of a Leverhulme Fellowship for the award of which the writer acknowledges her grateful thanks.

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#### DESCRIPTION OF PLATES

##### PLATE I

FIG. 1.—Granodiorite (192) with rims of potash feldspar around the quartz groups. Northern end of Slieve Gullion, west of Camlough reservoir. Ordinary light  $\times 14$ .

FIG. 2.—Granodiorite (338) with broad rims of potash feldspar around the quartz groups. Collected to the north of the Flurrybridge vent. Ordinary light  $\times 14$ .

FIG. 3.—Granodiorite (1622) with rims of micropegmatite around the quartz groups. Collected from the massive block of granodiorite (30 feet from the edge) within the Flurrybridge vent. Ordinary light  $\times 14$ .

FIG. 4.—Micrographic granodiorite (1617) from the upper horizon of transformed explosion breccia on Slieve Gullion. The quartz groups have rims of micropegmatite in which there is an inner irregular zone formed by replacement of quartz, and an outer zone of lace-like micropegmatite that has replaced plagioclase. Ordinary light  $\times 14$ .

## PLATE II

FIG. 5.—Micrographic granodiorite (1541) from the upper horizon of transformed explosion breccia on Slieve Gullion. The quartz groups are replaced by patches of irregular micropegmatite which are rimmed by lace-like micropegmatite developed at the expense of plagioclase. Ordinary light  $\times 14$ .

FIG. 6.—Micrographic granodiorite, as in FIG. 5, showing the micropegmatite more highly magnified. The relatively coarse-grained irregular micropegmatite replaces a quartz group and is margined by finer-grained lace-like micropegmatite developed from plagioclase. In the upper left-hand corner a residual core of plagioclase is seen in relation to the replacement rim of lace-like micropegmatite. Ordinary light  $\times 51$ .

FIG. 7.—Micropegmatitic granodiorite (1526) from the upper horizon on Slieve Gullion showing the replacement of a crystal of sodic plagioclase, residual from the initial granodiorite, by "quartz de corrosion," with the consequent conversion of the plagioclase to micropegmatite. Crossed nicols  $\times 22$ .

FIG. 8.—Micropegmatitic granodiorite (76) from the upper horizon on Slieve Gullion showing the replacement of a zoned crystal of sodic plagioclase by small crystals of oligoclase. Crossed nicols  $\times 22$ .

## DISCUSSION

P. A. GEIJER said that locally at the contacts of wide diabase dikes in the Swedish Pre-Cambrian they had encountered phenomena which were essentially identical with those just shown by Dr. Reynolds on the screen. Thus a gneissoid granite might be changed, within a width of a couple of metres from the contact, into a porphyritic rock with a micropegmatitic groundmass and carrying as "phenocrysts" the relict grains, mostly composite, of the granite's quartz and feldspar. Quartz grains, still retaining their undulatory extinction, exhibited typical corrosion embayments. There was no reason to suspect any material chemical change. They had interpreted those phenomena as due to the heating effect of the diabase intrusion. Miss Callisen had described a similar occurrence on the Danish island of Bornholm.

P. E. ESKOLA said that Dr. Reynolds' description of the gradual replacement of granodiorite by granophyre was most elucidating. In the Archaean, granitization of granodiorites led to granitoid but never to granophyric textures, whereas granophyres were common at the contacts of hypabyssal post-Archaean (Jotnian) olivine-dolerites with Jotnian sandstones, rapakivis, and older migmatites. The granophyres formed small dikes and veinlets near the contact in the older rocks, but also in the dolerite itself. They had apparently crystallized from palaeogenic magma that had originated by partial or complete anatexis of the older rocks. Now, in the hybrid rocks near the contacts, where the magma was imbibed in the country-rock, they found gradual replacement of the older minerals by the granophyre minerals just as had been described by Dr. Reynolds. As those phenomena occurred in a zone influenced by liquid basaltic (doleritic) magma which, while liquid, had certainly temperatures far above the solidus of granites, they afforded an excellent evidence of granitization by means of anatexis, which meant re-melting. The evidence was the more convincing, as granophyric texture was characteristic of rhyolites, quartz-porphyrries, granite-porphyrries and other assuredly magmatic rocks of volcanic or hypabyssal character, but did not occur either in metamorphic or in truly deep-seated magmatic rocks, excepting hybrid rocks.

H. VON ECKERMANN said that Dr. Reynolds had asked Professor Eskola how he explained the removal of Fe and Mg if magmatic granite were responsible for the granitization. He was returning the question to Dr. Reynolds by asking what had become of the Fe and Mg lost during her proposed transformation of the Caledonian granodiorite into granophyre.

DORIS L. REYNOLDS, in reply to Dr. von Eckermann, said that it was very probable that the Fe, Mg and Ca lost from the granodiorite during its transformation to granophyre had migrated into the adjoining dolerite sills. For this reason chemical analyses of the middles and edges of dolerite sills adjoining transformed granodiorite were being made; some of these analyses had, in fact, already been made. At present, however, there was no standard for comparison since there were no chemical analyses of the middles and edges of comparable but unaltered dolerite sills or dikes. She had, therefore, collected specimens from the middles and edges of various members of the Arran dike-swarm, in order that they might also be analysed and a reliable standard of reference thus be established.



# SOME OBSERVATIONS ON HOMOGENIZATION AND ON GEOCHEMICAL DISCONTINUITIES IN GRANITIC AREAS

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## ABSTRACT

The structural and textural peculiarities of two different types of granites—mega-porphyritic and even-grained—are correlated with the tectonic style of the sedimentary formations within which they are emplaced. Mega-porphyritic granites are found to be products of transformation of sediments of fairly equal competence exhibiting harmonious isoclinal folding. On the other hand even-grained granites are products of transformation of sediments of varying competence that show crumpling and disorderly folding. In either case the transformation that led to granite formation resulted from metasomatic changes dependent on small introductions from an external source, chemical interchanges amongst the rocks themselves, and expulsions of excess materials. As homogenization of the granite masses proceeded, the expelled constituents became fixed within limestones and basaltic rocks intercalated in the sedimentary series, and in skarn of basic front type. Similarly expelled ore constituents have enriched original poorer sedimentary ore deposits at several different stages. The lack of characteristic and related proportions between the trace elements within the ores that have been found in spectrographic investigations is believed to be an inheritance from the sedimentary rocks from which the constituents were derived.

## I. INTRODUCTION

IN a short review on ore formation (1941a), the writer directed attention to the fact that the minor chemical constituents which jointly form but 2·24 per cent by weight of the mean composition of the earth's crust, as calculated by Clarke, Washington, Vogt, Vernadsky, and Fersman, include nearly all those metals that are most ardently sought after. It is obvious that these metals, which individually rarely average more than 0·01 per cent by weight of the earth's crust, become available for industrial exploitation only where they have been highly concentrated by natural processes that have worked with powerful efficiency against the universal tendency to dispersal.

Following suggestions of Vernadsky (1924) and Goldschmidt (1922), the writer drew attention to the fact that the most effective initiator of such concentration of dispersed materials is the disintegration of rocks by weathering. After such disintegration the individual constituents of the rocks become separated from one another and concentrated (1) by differential solution and evaporation, or (2) by some form of sorting during transport, or (3) by organic agencies. In the third case certain chemical constituents become concentrated by the activity of living organisms which may (a) accumulate them within their tissues or secretions, (b) utilize them for the construction of their inner skeletons or outer shells or carapaces, or (c) concentrate them either in their excreta or as a result of chemical reactions in the course of their final decay. Amongst the organisms that have brought about the separation and concentration of chemical constituents, the microzoa and microphyta, with their innumerable individuals, rapid successions of generations and varied associations, and with geological time at their disposal, have played a very important rôle. Although organic agencies are the most potent in bringing about the separation and concentration of special chemical constituents at widespread localities, yet such concentrates are preserved within the sedimentary pile only when they are deposited under special and balanced conditions of depth, water-chemistry, and rate of general sedimentation. If these conditions are not fulfilled, the material accumulated by organic agencies is redissolved either whilst on its way to the site of sedimentation, or immediately after deposition.

The separation and concentration of chemical constituents by the three processes enumerated above leads to the development of geochemical discontinuities within the sedimentary suites of which these products form constituent parts. These discontinuities occur both along horizontal planes and through

vertical sections. The most pronounced ones are those due to organic agencies whereby the most varied constituents, and occasionally even rare elements (lanthanides, actinides, etc.) may be accumulated in appreciable amounts. The maximum intensities of separation and concentration of chemical constituents in general occur as sequels to orogenic culminations, and become strongly accentuated where there are related glaciations, since the latter contribute to more vigorous and thorough disintegration of the pre-existing rocks.

The writer has elsewhere (1941*b*, 1943) pointed out that the Actualistic (Uniformitarian) Principle may be applicable throughout the whole range of the geological formations and orogenic belts that constitute the earth's crust and represent vestiges of its history from far distant Pre-Cambrian times. If this be so then sedimentation of the kinds referred to above, with similar separations and concentrations, should have gone on throughout the whole of known geological history, and have given rise throughout to geochemical discontinuities. Now as investigations are pushed farther back through geological time it is found that easily recognizable sediments become scarcer. Not only is there a general decrease in the amount of obvious sedimentary material, but it has been supposed that sediments accumulated by organic agencies, or as a result of chemical precipitation, are completely lacking within the early Pre-Cambrian and "Archæan" rocks. From this supposition the conclusion has been drawn that the conditions under which sediments were then formed were radically different from those of to-day. The writer has repeatedly tried to show that this is not the case, and in particular that sediments accumulated by organic agencies are present within some of the oldest known formations and orogenic belts (1943, 1946), but that they have been camouflaged as a result of metamorphic reactions and recrystallization. The present communication is concerned with the problem of what has happened to such sediments in those parts of orogenic belts where, from geometrical considerations they would be expected to occur, but where, in actual fact, granite appears.

## II. METHOD OF INVESTIGATION

In order to solve the problem as to what has become of rocks that once extended through those parts of orogenic belts where granite now appears, every field investigation of such areas must include observations relating to three fundamental aspects of the problem:—

(1) The first relates to the fact that geosynclinal sediments develop different styles of folding according to their individual composition and competence, and dependent on the intensity of the tectonic forces. It is necessary to discover whether the granite does or does not show any structural or textural peculiarities that reflect the style of deformation that characterized the sediments that originally occupied the same space.

(2) The second relates to the fact that geosynclinal sediments always contain intercalations, at various stratigraphic horizons, of basic volcanic rocks—the geosynclinal basalts and ophiolites. These rocks differ, both physically and chemically, from the average sediments, and it is necessary to discover whether they have had any influence on the appearance of the granite that has taken their place.

(3) Thirdly it is necessary to discover whether it is possible to trace concentrates of minor constituents, comparable with those resulting from organic sedimentation, which provide evidence of their original zonal or regional distribution.

As already pointed out by Goldschmidt (1922), the emplacement of granite, whatever the mechanism may have been, represents a homogenization of the earth's crust. The three methods, listed above, of investigating the problem of the vanished geosynclinal sediments are focused on the discovery as to just how perfect this homogenization may be.

For the purpose of investigating the problems outlined above only granitic areas of important regional dimensions are practicable, such as those emplaced within orogenic belts that have rather incorrectly been termed "syntectonic." There are two different types of such regional granitic areas to be considered, both of which, at least in some cases, show a persistent uniform development throughout the whole of their exposed extent. These are the coarse-grained mega-porphyritic granites on the one



hand, and the medium even-grained granites on the other. Both these varieties of granite are discussed in the following sections of the paper, and all the existing data relating to the Swedish examples have been utilized in a demonstration of the application of the methods of investigation here suggested.

### III. COARSE-GRAINED MEGA-PORPHYRITIC GRANITES

The rapakivi granites, though they share many features in common with this group, do not belong here because, being long post-orogenic in their emplacement, they exhibit distinctly different relationships which have already been discussed by the writer (1938) in the light of the extensive literature that they have evoked. Yet the rapakivi granites are comparable with the present group in that their closely packed phenocrysts of pink potash feldspar were formed at high levels and are by no means witnesses of a deep-seated intratelluric origin.

The granites of the group to be discussed are characterized by closely packed rounded phenocrysts of perthitic potash feldspar (microcline) up to 5 and 10 cms. across, which in some cases are grayish white in colour, and in others pink. These phenocrysts are embedded in a scant mesostasis consisting of yellowish plagioclase feldspar, glomerogranular groups of brownish or grayish quartz, with subordinate mafic constituents, biotite and/or hornblende, and a small amount of ore minerals. The colour index of these rocks is low and somewhat variable, the general impression being that of a light grayish colour in the one case, and a dirty pink in the other. On account of the rounded form of the feldspar phenocrysts, these rocks have come to be known as augen-granites, whilst in those cases where the feldspar "eyes" are most closely packed, so that there is a minimum of medium-grained mesostasis filling interspaces only, the rocks may be termed gross granites. The "eyes" are sometimes composed of three or four irregularly intergrown individuals with rows of inclusions of quartz grains that increase in grain size from the centre outward. The rows of quartz inclusions are more or less straight, and have a common regional orientation. Textures that are commonly attributed to flow movement within a supposed magma are sometimes found. Bead-like strings of phenocrysts, arranged with a perfect parallelism, that attract the attention when viewed in favourable directions along the strike, are usually interpreted in this way. Sudden transitions to "augen-gneiss" are common in the border regions of the granites, and in the vicinity of inclusions of true gneiss. Such may be described as marginal phenomena. Distinct areas in which the phenocrysts have a disorderly arrangement are also found within the granites; these appear as islands surrounded by granite in which there is a general parallel orientation. Streaks of medium even-grained granite are also sparsely distributed through the mega-porphyrritic variety and give the impression of representing later mobilizations, yet without presenting any real proofs of being younger intrusions. Pink mega-porphyrritic granites, which owe their colour to that of the phenocrysts, are sometimes present within areas of gray gross granites and display a regional distribution without showing any evidence of a difference in time or mode of emplacement. Gray gross granites within areas of red gross granites, however, are hardly ever found; where a gray variety does appear within the red gross granite it is usually much finer grained.

There is one big area of each of the two varieties of mega-porphyrritic granite within the Pre-Cambrian of Fennoscandia. The gray mega-porphyrritic Revsund granite, with its subordinate pink variety, the Björna granite, occurs in the northern half of middle Sweden. It has a maximum length of 350 km. extending in a N-S direction, and a maximum width of 180 km. in an E-W direction. The pink mega-porphyrritic Filipstad granite occurring in the southern half of middle Sweden is much less uniform than the Revsund granite. It has a N-S length of about 250 km., and a very variable E-W breadth. Both the Revsund and the Filipstad granites appear to be of Gothocarelian age. The chemical composition of both these granites is rather uniform. The chemical analyses (cf. Larsson, 1932) conform with the criteria that have been adopted for the recognition of "magmatic" rocks with  $al < (c + alk)$ . The potash ratio ( $k$ ) is somewhat more pronounced in the Filipstad granite whilst the magnesia ratio ( $mg$ ) is higher in the Revsund granite. The degree of oxidation ( $og$ ) is somewhat stronger in the Filipstad granite, the average of which ( $83.7$ ) approaches the average for all Swedish granites ( $83.1$ , Landergren, 1948, p. 25).

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Now in both these granitic areas mega-porphyritic granites, characterized by bead-like strings of phenocrysts embedded in a statistically isotropic and fairly coarse-grained mesostasis, show sudden transitions to augen-gneisses both in the direction of the bordering rocks and towards foliated inclusions. In the augen-gneisses the "eyes" of feldspar, with quartz in their angles, form discontinuous strings within a well foliated biotite-rich mesostasis. Marginward the augen-gneisses are bordered by banded gneisses or arterites, the so-called "lit-par-lit injection" gneisses, in which white and mostly straight even and fine-grained feldspathic bands contrast sharply with the dark coloured well foliated mica-schists which contain traces of carbonaceous material. Where they adjoin the augen-gneisses the feldspathic bands occasionally show bulges of somewhat coarser grain size. Away from the augen-gneisses the feldspathic bands gradually taper out and the arteritic rocks pass into foliated mica-schists.

The characteristics outlined above have been described so often that it perhaps seems a waste of time and space to record them here again. There are, however, some further points of general interest which make it possible to apply the methods of investigation outlined in the preceding section of the paper, and from which the fate of the country rocks that once occupied the space now filled by granite can be deduced. The bordering mica-schists, in which muscovite is the dominant mica, show an alternation of layers very rich in mica with fine-grained layers, composed of quartz and some plagioclase, which are almost free from mica. Whether this layering represents primary bedding of the original sedimentary rock, or whether it has resulted from tectonic deformation, is difficult to decide, but is of subordinate importance in the present connection, as is the question as to how far the chemical composition of the initial rock was changed when it was transformed into mica-schist. It is clear, however, that the strings of phenocrysts within the mega-porphyritic granite, the strings of augen in the augen-gneiss, and the arteritic rocks all follow the same regional trend as the foliation of the mica-schists. From the disposition of the trend lines in the field, moreover, it can be seen that the linear structures of the various rocks reproduce the fold structures of the vanished portion of the mica-schists. The pitch of the fold axes is steep, and this field observation in conjunction with the parallelism of the linear structures over wide areas indicates that the style of folding was isoclinal.

After the isoclinal folding of the sedimentary antecedents of the rock series of which the mica-schists form part there was recrystallization, as is evidenced by the fact that the mica flakes of the present-day schists follow the curves of the crests and troughs of the folds without distortion. With a renewal of tectonic deformation—no longer of ordinary sediments but of metamorphic rocks—the adjustments involved in further folding were made along closely spaced glide planes within the mica-schists. Along these planes the crystals were distorted. Concomitantly, and probably resultant on the shearing stress, there was a migration of chemical elements, including femic materials, from the deformed crystal lattices along the glide planes into the less disturbed layers between, where biotite grew in consequence. It is also possible that the deformed material was to some extent albitized at this time. In this way the banding of the mica-schists, with an alternation of narrow micaceous and quartzo-feldspathic layers, was enhanced.

With the cessation of tectonic pressure and movements the second phase in the evolution of the present-day rocks commenced, and where the temperature was highest the arteritic or banded gneisses were evolved. Now the feldspathic bands of the banded gneisses cannot be explained as magmatic (lit-par-lit) injections because they include biotite-rich streaks of mica-schist origin which still retain an undisturbed parallelism with the bordering micaceous bands. Nor can they be explained as a result of some process of exudation because the intervening mica-schist bands do not show the necessary decrease in their potash content as judged by the proportion of mica present. Examination of some of the feldspathic bands reveals the fact that they correspond to several quartzo-feldspathic layers of the ancestral mica-schist which were originally separated from one another by thin mica-rich layers (Plate I, Fig. 1). Relics of the latter still remain in undisturbed position within the broad feldspathic bands, but they are now wholly composed of biotite of coarser grain size. From this evidence it can be deduced that the feldspathic bands of the arteritic gneisses have each been formed from several



adjacent layers of the mica-schist as a result of introduction into the quartzo-feldspathic layers of elements necessary for the growth of potash feldspar, and expulsion from the intervening micaceous layers of calcic and other excess materials. This expulsion of materials can in part be correlated with an enrichment in Fe and Mg both of the micaceous bands of the arteritic gneisses, and of the relics of almost vanished micaceous layers within the feldspathic bands; the enrichment being evidenced by a preponderance of biotite as compared with a preponderance of muscovite in the initial mica-schists. The materials that were introduced in the evolution of the arteritic feldspathic bands would find pathways through the imperfect crystal lattices of the distorted minerals along the glide planes referred to above.

The third phase in the evolution of the present-day rocks began with the crystallization of potash feldspar at localized nodes, that now appear as bulges, along the feldspathic bands of the arteritic gneisses (Plate I, Fig. 2). The boudinée form of such bands suggests that this third phase of development was the result of further tectonic movements. On account of the increased rigidity of the rocks consequent on the feldspathization, however, the old glide planes failed to continue to function, and the rigidified feldspathic bands reacted with boudinage. This disruption of the competent feldspathic bands would be accompanied by the characteristic flowage of the adjacent micaceous layers, the foliation of which would come to curve round the boudins. Such movements would give rise to loci of relative positive and negative pressure along the feldspathic bands, the latter corresponding to the boudins, and the former to the points of inflowage of the micaceous bands between the boudins. At the loci of relative negative pressure recrystallization would be particularly favoured and take place concomitantly with the disruption of the bands. Where there was complete disruption of the bands each isolated boudin is now represented by a feldspathic "eye" around which the adjacent mica flakes bend in parallelism with its margins. In this way the augen-gneiss with its bead-like strings of augen was evolved. Where the disruption was only partial the feldspathic bands now show bulges, which are continued as strings of augen in the augen-gneiss (Plate I, Figs. 3 and 4). The boundary between augen-gneiss and banded gneiss, however, is readily discernible and has a sinuous form.

At the time when the banded gneisses were transformed to augen-gneiss, the basaltic sheets that were intercalated in the original geosynclinal sediments and that had escaped from stronger tectonic deformation underwent an allied change. Big rounded phenoblasts of potash feldspar, of the same order of size as the augen of the augen-gneisses, grew within them. Within the basaltic rocks, however, the potash feldspar phenoblasts have a disorderly arrangement that stands in contrast with the orderly disposition of the augen in the augen-gneisses. The growth of the feldspar phenoblasts within both the gneiss and the basalts led to a further expulsion of calcic constituents. In consequence basic fronts began to form, quartz-diorite-gneisses developed as a result of the concentration of such displaced constituents within the gneisses, whilst the fixation of these constituents within the basaltic rocks gave rise to amphibolites, amphibole-gabbros, etc.

With the cessation of the movements that led to the evolution of augen-gneiss the fourth phase of transformation gave rise to the mega-porphyritic or augen-granites. At this time the expulsion of calcic and other superfluous constituents culminated, and accumulations of skarn along the margins of the granite reached their maximum concentration and diversity. Within the mega-porphyritic granite, areas within which strings of phenoblasts are still discernible (Plate I, Fig. 5) represent relics of the replaced augen-gneiss, whilst others in which the phenoblasts show an irregular distribution represent the pre-existing but now transformed basalts (Plate I, Fig. 6). Apart from such textural differences, however, the granite evolved from augen-gneiss and basalt is identical both in composition and structure. In the mega-porphyritic granite homogenization is apparently completed. The contact between the mega-porphyritic granite and the augen-gneiss at the present surface of the earth is quite well defined, though irregular, with "inclusions," or rather relics, of augen- and banded-gneiss still remaining within the margin of the mega-porphyritic granite. Occasional overlaps of the four phases such as these confirm the sequence of events.

The gray or red colour of the final granite is correlatable with the relative abundance or paucity of carbonaceous material in the initial sediments. Where carbonaceous material was relatively abundant within the initial sediments the granite evolved from them is gray, whereas if the parental sediments were deposited under oxidizing conditions this is now evidenced by the presence of trivalent iron, as red colouring matter, within the feldspar phenoblasts.

From this study of the mega-porphyritic granites and the associated gneisses it is clear that the phenocrysts within the granite represent a further stage in the evolution of the augen in the augen-gneiss. Thus, such phenocrysts are by no means witnesses of a deep-seated origin within a magma-basin. On the contrary they have been formed within solid rocks and, as is indicated by the tectonic style that has brought about their evolution, at relatively high levels in the earth's crust.

The intercalations of medium even-grained, or aplitic, granite within these areas of gross granite may have been formed at the expense of a feldspar-bearing rock, other than the mica-schists, whose evolution and consequent structure and composition were fixed during an earlier epoch, and which, in consequence, responded differently to tectonic deformation. Perhaps the aplitic granite, which sometimes retains relict bedded structures, may have resulted from the granitization of a leptitic rock suite.

Now along the border of the Revsund granite, and outside its margins, there are ore concentrations associated with highly varied accumulations of skarn that belong to its basic front. The sulphides and arsenides in original and poorer sedimentary ore deposits have here been enriched at several different periods, and their order of fixation has been thoroughly investigated in the Boliden and neighbouring mining areas on the northern border of the granite (S. Gavelin, 1939; Ödman, 1941, *et alii*). The sequence of the enriching emplacements can be best explained in connection with the different phases of granitization within the area to the south, and in particular with the expulsions of caferic and other excess materials from this area. A geochemical investigation of the minor (metallic) constituents within the sulphide ores of the different mining fields has shown that there are no characteristic combinations or proportions of these elements within the different areas (S. Gavelin and Gabrielson, 1947). On the contrary even the ores of one and the same mine are completely lacking in any common and characteristic proportions between the minor elements. They thus show serious geochemical discontinuities which are completely inharmonious with any supposition that the ores had a pneumatolytic or hydrothermal origin related to magmatic differentiation (see Conclusions, p. 40). On the other hand, if the ores represent one of the results of basic front action they should reflect the initial conditions that obtained within the areas from which they were displaced with respect to those minor elements which are related to the leading cations of the ore sulphides through alliances controlled by isomorphism and other properties. They should, in fact, reflect the geochemical discontinuities of the sedimentary areas that have been granitized, particularly with respect to those minor elements which succumb to migration in company with the caferics of the basic front. The geochemical discontinuities of the ore and skarn deposits represent a step that was taken on the way towards homogenization within the replacing granites. Geochemical discontinuities still remaining within the otherwise homogenized granite may probably be accounted for geochemically as concentrates of lithophile elements approximately on their original site of accumulation.

Similarly, spectrographic investigations of the minor constituents (Cd, Ga, In, Ge, Mn, Fe, Co) within the zinc blende ores from various Swedish occurrences and sulphide mines reveal geochemical discontinuities (Gabrielson, 1945). Within the various units there are no correlations between these constituents such as would indicate a common origin from residual magmatic solutions of a pneumatolytic or hydrothermal kind, and this remains true even when possible telescoping effects are kept in mind; there are indeed some indications of fixation of zinc blende at higher and lower temperatures. Those occurrences of zinc blende ores that can be correlated with the emplacement of the Filipstad granite reveal proportions and discontinuities that can be explained only by relating them to the initial sedimentary rocks from which the Filipstad granite was evolved.



## IV. MEDIUM EVEN-GRAINED GRANITES

The Uppsala granite of eastern Central Sweden, a rather homogeneous rock with a sombre grey colour, has an areal extent of approximately 150 km. in a N-S direction, and 120 km. in an E-W direction. White, somewhat zoned plagioclase, with a composition that lies within the limits of andesine, is the dominant mineral. Together with pale coloured microcline and quartz that mostly has a bluish colour, it constitutes the felsic part of the rock, whilst biotite and bluish green hornblende rarely with diopsidic cores, and small amounts of titanomagnetite and apatite, make up the abundant mafic portion. In the southern and western parts of the area the pink Wänge granite is the dominant rock, but it presents no decided evidence such as would indicate that it was emplaced before or after the grey granite. Westward the predominant grey granite merges into a more leucocratic variety, known as the Sala granite, which is characterized by oligoclase. The typical grey granite commonly has small basic inclusions. All three varieties show a similar degree of oxidation ( $og = 81.09$ ) which is close to the average for Swedish leptitic rocks ( $og = 81.2$ ). Apart from this their chemical characteristics are those appropriate to supposedly true "magmatic" rocks, *i.e.*,  $al - (c + alk) \leq 0$ , with no *cor* in the norm. The bulk chemical composition of the various granites is shown by the chemical analyses listed in W. Larsson's (1932) well-known compilation of analyses of Swedish rocks.

The margins of this composite granite mass, which belongs to the Svecofennian belt, are not well defined, the granite passing to a gneissose variety containing irregularly distributed inclusions of older leptitic rocks which exhibit various degrees of granitization and tectonization. Moreover, later rather homogeneous granites encroach upon its area. These are of the statistically isotropic Stockholm granite type, dominantly potassic ( $k = 0.66$ ,  $mg = 0.28$ ), with a stronger degree of oxidation ( $og = 85.6$ ) than the Uppsala and related granites, and always with appreciable normative corundum ( $al - (c + alk) > 0$ ).

Now as indicated above, the granite area proper consists of a number of sub-areas of perfectly homogeneous statistically isotropic varieties, with small and scanty masses of gabbro or diorite, of earlier crystallization than the granites, occurring as occasional and sparse inclusions. The main sub-areas of granites are separated from one another by more or less broad bands of gneisses with a predominant grey colour. From the geological map of the area (text-fig. 1) it can be seen that these bands of gneiss strike in E-W and N-S directions, the two different trends being connected by curved bands of similar rock. The disposition of the bands of gneiss on the map presents a clear picture of a projection, on the topographic surface, of broad folds pitching steeply eastward and modified by differential sliding of the beds along the fold-axes. The bands with an E-W strike represent the limbs of the folds, and those with a N-S strike the crests and troughs. The picture is a replica of the structure of the outer Stockholm archipelago (Holmquist, 1910; Sundius, 1939) situated immediately to the south of the area under discussion. Associated with the gneisses, and following the same trend, are relict bands of leptitic rocks, granulites and mica-schists. From the disposition of these relics it can be deduced that the original folded framework was composed of leptitic rocks essentially at the crests and troughs of the folds, with granulites and mica-schists forming the limbs. These rocks, since they include quartzites, limestones, and rhythmically banded iron ores at various horizons, represent a mixed suite of geosynclinal sediments of early Svecofennian age. All the rocks are now, of course, more or less transformed as a result of metasomatic and other processes.

The first metasomatic alteration of this sedimentary suite, the feldspathization that resulted in leptitization, was subsequent to the principal folding, but movements later than the leptitization took place especially within the limbs of the folds. At a later stage of transformation the leptitic rocks and schists, together with intercalated rocks of limestone-origin and rarer basic intrusive sheets, were largely transformed to grey or red gneiss. The transformation of leptitic rocks to gneiss resulted from the progressive development of coarser feldspathic material along their foliation planes. Elongated slabs of leptitic rocks, more or less transformed to gneiss by metasomatic processes, and showing more and more marked transformation the further they are situated from the relict leptitic framework, still

### PART III : METASOMATIC PROCESSES IN METAMORPHISM

remain within the gneiss. The feldspathic material also increases in amount as the distance from unaltered schist relics becomes greater, gradually replacing them without effacing their original foliation. Thus, by successive stages the leptitic and schistose rocks grade to gneiss in which the gneissose texture is an exact copy of the foliation or bedding planes of the original rocks. It is evident, therefore, that this transformation has been effected, without melting, as a result of substitution dependent on migrations of chemical elements. Finally, by further development of quartzo-feldspathic material, the foliation planes become obliterated and the gneiss grades to the homogeneous statistically isotropic granites.

The basic rock bodies (recorded on the older maps as greenstones, dioritic and quartz-dioritic schists, etc., or as hornblende-gabbro) that are so common within the gneisses, and which represent limestones and more rarely basic intrusive sheets that were present in the ancestral sediments, are also

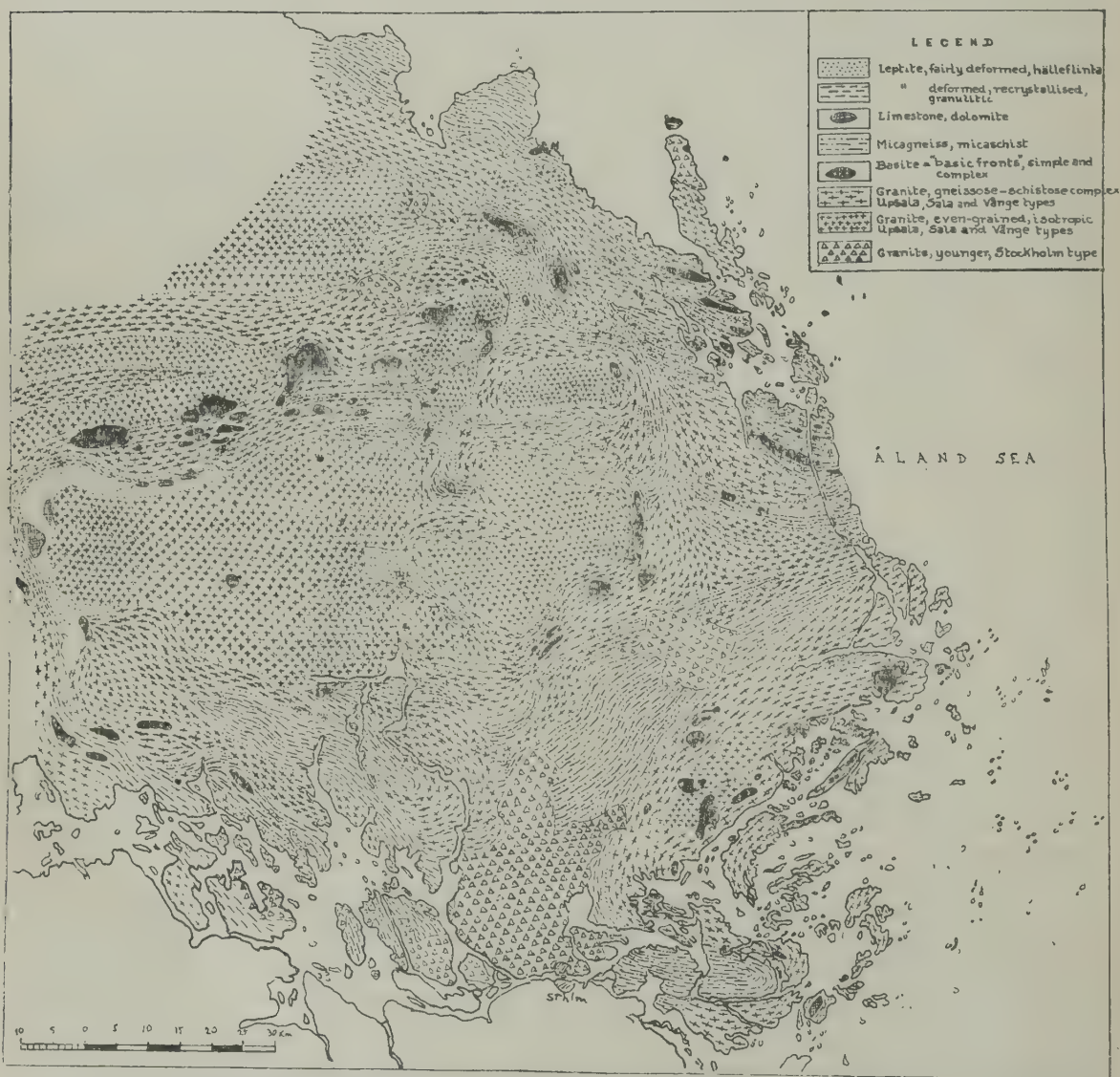


FIG. 1.—Uppsala Granite Area compiled after H. G. Högbom, A. E. Törnebohm, the official geological map sheets and recent field observations.



gradually replaced by quartzo-feldspathic material, and become very scarce within the even-grained granites. Vein-like replacements of quartzo-feldspathic material appear within the basic bodies and gradually increase in width until the rocks acquire an agmatite-like appearance, and give an erroneous impression of having been blasted into angular fragments. In other instances the basic bodies gradually disappear as a result of uniform replacement. In either case mafic materials are displaced and emigrate. The mineralization of distal limestones, with the evolution of skarn of basic front type, is probably to be correlated with such displacement of mafic constituents from proximal granitized basic rocks.

That the homogeneous even-grained granites represent replacements of pre-existing rocks of varied facies is apparent from their regular position within and conformity with the pattern of the steeply pitching folds evidenced by the distribution of the gneisses with their relict framework of leptytic rocks and schists. This conclusion is supported by detailed transitions ranging from leptytic rocks and schists, through gneisses to granite. Within the granite homogenization has finally obliterated the last vestiges of former folds.

The "greenstone" bodies aggregated within the bands of gneiss, to which reference has just been made, and more especially those schistose varieties with the composition of quartz-diorite, diorite and amphibolite, are relics of manifestations of "basic front" action within the calcareous sediments of the initial sedimentary framework. More rarely such "greenstones" represent relics of basic and ophiolitic intrusive sheets that were present within the original geosynclinal sediments, but which are now strongly transformed and basified by "basic front" action. The limestones and basic igneous bodies have twice been subjected to metasomatic processes dependent on "basic front" action, that is to the fixation of mafic and other materials displaced from rocks undergoing granitization. This took place at the initial feldspathization or "leptytization" of appropriate sediments, and secondly at the time of the neighbouring areal granitization which was an act of homogenization by metasomatism.

The granitization cannot be attributed to the action of "granitic solutions" of any kind of magmatic origin. So many and varied were the pre-existing rocks that are now transformed to granite that if such solutions had existed they must have been incessantly modified and altered in composition after each new rock variety was granitized. Under such circumstances the postulated solutions could not have retained their individuality and energetic potentials sufficiently to bring about homogenization. In such cases it is absurd to speak of "solutions," and especially of "granitic solutions."

The mineral composition of the final granite, and the dispersed "inclusions" of gabbro and diorite within it suggest that the original sedimentary rocks included a not too subordinate proportion of limestones. For the eventual development of an even-grained granite it is necessary that the original sediments should be either completely and uniformly feldspathized, *i.e.*, leptytized, or crumpled into irregular micro-folds during the general folding. In the first case lack of diversified structures would favour an even granitization. In the second case micro-folding and micro-crumpling of the sediments, especially in the presence of beds of limestone which on transformation would lead to volume change, would prevent the formation of orthoigneous rocks like those described in the preceding section of the paper, and in consequence favour an even-grained granitization. Judging from knowledge of the diversity of the rock types involved it is improbable that the initial leptytization could have been complete and uniform throughout. On the other hand, if in the original sediments there was an alteration of competent and incompetent sediments, *i.e.*, of psammitic and pelitic sediments, as there appears to have been, then the initial folding would have been likely to give rise to crumpling. Indeed vestiges of crumpling are plentiful within the relict areas of leptytic rocks, mica-schists and granulites.

In the Uppsala granite area one is able to present more perfect evidence of the lack of homogeneity of the granites with respect to their minor geochemical characteristics than in the case of the Revsund and Filipstad granites, a lack of homogeneity which is incompatible with a supposed magmatic origin of the rock assemblage. In the zinc blende ores that are mined in ore fields well within the granitized area the minor constituents that have common affinities with Zn show no agreement or co-ordination

of any kind that would suggest that the ores were derived from pneumatolytic sources or from granitic residual solutions; on the contrary they indicate different sources of origin. On the other hand, the minor constituents of the old "leptites" characteristically show geochemical discontinuities, and this peculiarity, with some small modifications, has been inherited by the granites which replace them (Lundegårdh, 1946). Such an inheritance of geochemical discontinuities can hardly be explained as a result of assimilation of the leptites by molten granite magma because a detailed homogenization of the end product would be inevitable at the necessary high temperatures. Similar geochemical discontinuities in the distribution of the minor constituents within granites have been discovered in the course of important Finnish investigations (Sahama, 1941), but have not hitherto received sufficient explanation. The recent orthodox suggestions (Rankama, 1946) that such discontinuities represent the effects of late differentiation from magmatic sources do not conform with the geological field conditions since these indicate that the rocks under consideration were formed at a high level in the earth's crust.

#### V. CONCLUSIONS

It is perhaps of interest to recall that geochemistry began in the United States by a search within the igneous rocks for the minor constituents which jointly form but 2.24 per cent by weight of the earth's crust. Particular combinations of these elements in small amounts and appropriate proportions should supposedly characterize individual "magmatic" provinces. Rocks that show a "consanguinity" were regarded as having been derived from a common magmatic stock, and as having become individualized through some process of magmatic differentiation that operated within a deep-seated "magma-chamber" or within less deep-seated subsidiary reservoirs. The first attempt to decipher these inter-relations remained without decisive success, but the attempt was resumed and amplified after progress in and improvement of spectrographic methods, and after Goldschmidt's investigations of the laws of geochemical distribution of the elements within the earth's crust (1922-38, 1937). If the magmatic differentiation hypothesis is tenable then a uniform distribution of stable combinations of the minor elements throughout individual rocks of a "province" is to be expected, with characteristic but related deviations between the various members of the "province." Now extensive areas of superficially uniform granitic rocks provide excellent possibilities for investigating whether such detailed homogeneity is indeed a fact. From the foregoing sections of this paper it will be apparent that, quite apart from the field evidence that the Swedish granites under discussion have a replacement origin, such geochemical data as have already been accumulated are incompatible with an origin by any process of crystal differentiation either for the granites or for the associated ores.

A critical examination of all the available evidence relating to extensive areas of mega-porphyritic and even-grained granites in Sweden leads to the following conclusions with respect to the three problems that were presented in section II of this paper:—

(1) Granites emplaced within sediments of fairly equal competence that exhibit harmonious isoclinal folding are of mega-porphyritic type. On the other hand granites emplaced within sediments of varying competence that show crumpling and disorderly folding are of even-grained type.

(2) Petrographic and chemical contrasts between the various members of the original sedimentary and associated rocks do not influence the main trend of the textural development of granites emplaced within them. Aberrant types, such as basic igneous and metasomatic rocks, undergo textural (and chemical) transformations closely similar to those developed within the prevailing sedimentary types, and induced within them by the predominant tectonic style.

(3) Well bedded sedimentary series are characterized by marked geochemical discontinuities both in the horizontal and vertical directions. Granites, together with their "basic fronts," emplaced within such sediments display corresponding geochemical discontinuities of the minor chemical elements suggestive of an inheritance from pre-existing sedimentary rocks.

All three of these conclusions, which still require and deserve manifold checks, both in the field and in the laboratory, are compatible neither with a magmatic origin of the granites, dependent on



the intrusion of molten silicate solutions from the depths below, nor with the action of "granitic solutions" of any kind.

In connection with the suggested relationship between the geochemical discontinuities of the minor constituents within granites and the sedimentary rocks within which they are emplaced, increased systematic investigations of the geochemistry of sedimentary rocks are required. This aspect of geochemistry, in its inter-relations with granitic emplacements, has been greatly neglected. Moreover, in interpreting geochemical investigations that are concerned with the distribution of the minor constituents within the various rocks of the earth's crust it should not be forgotten that these constituents which form but 2-24 per cent of the earth's crust by weight form an even smaller percentage by volume. They constitute but a very small proportion of the 10 per cent of volume occupied by the common cations within minerals. They are camouflaged, captured, or dispersed within a great many different crystal lattices and are probably capable of migrating only as a result of radical destruction of these lattices. In consequence it is possible for geochemical discontinuities of the minor constituents, once formed and fixed by mineralization, to persist within the final granite as witnesses of its evolution.

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### PART III : METASOMATIC PROCESSES IN METAMORPHISM

#### DESCRIPTION OF PLATE

*Stages in the Evolution of Augen-gneiss and Mega-porphyritic Granite. The Northern Border of the Revsund Area.* (Photographs of field outcrops, by courtesy of Dr. S. Gavelin.)

FIG. 1.—A feldspathic band, in banded-gneiss ("lit-par-lit"), retaining relics of the banded structure of the mica-schist it replaces. The feldspathic band is about 12 cm. broad. (1/8 natural size).

FIG. 2.—Banded-gneiss in which boudinage has given rise to bulges along the feldspathic bands. Each major division of the scale equals 10 cm. (1/8.)

FIG. 3.—Banded-gneiss in which feldspathic bands with bulges can be seen to continue as strings of augen; the result of intense disruption accompanied by further recrystallization of the feldspathic bands. The scale is about 20 cm. long (1/6).

FIG. 4.—Augen-gneiss with remnants of boudinée feldspathic bands; a further stage of disruption and transformation of the feldspathic bands than that shown in FIG. 3. Scale as in FIG. 2 (1/8).

FIG. 5.—Mega-porphyritic granite with strings of phenoblasts; a relict structure from antecedent augen-gneiss. Scale as in FIG. 6 (1/12).

FIG. 6.—Mega-porphyritic granite with an irregular arrangement of phenoblasts; the result of transformation of basaltic rock. The minor divisions of the scale equal 1 cm. (1/12).

#### DISCUSSION

THE CHAIRMAN, E. S. LARSEN, was reminded by Professor Backlund's paper of a granite exposed in a tunnel near Ware, Massachusetts. In this tunnel gently dipping micaceous schists were cut by a granite mass over a mile across. Near the contacts with the granite the schists contained lenses of granite several inches thick that were flat, parallel to the bedding and schistosity. The schistosity had not been bent or distorted by the granite as it must have been if the granite had been injected.

The granite-schist contact was sharp and it cut across the schistosity, but the granite showed a distinct but faint layering parallel to that of the schists. Plain layers of mica in the granite were essentially like those of the schist. The layering was present across the mass and was parallel to that of the neighbouring schist.

A. F. BUDDINGTON said he would like to ask a question for information. Could Dr. Reynolds tell them whether Dr. Backlund had anywhere published his ideas on the origin of the major metallic constituents of the ore deposits? It was obviously difficult to discuss the hypothesis which had been presented relative to the significance of the minor constituents without knowing how it fitted into the picture of the major constituents.

DORIS L. REYNOLDS in reply to Professor Buddington, said that Professor Backlund explained both the major and the minor metallic constituents of the ore deposits to which he refers as elements driven forward with the mafic materials of the basic front. She suggested that it would be more satisfactory if the discussion arising out of his paper were to be referred to Professor Backlund himself for replies that could be incorporated into the final report.

F. F. GROUT said it would be most presumptuous for him to discuss the evidence of replacement in an area he had not seen. There was a question, however, as to one assumption that appeared to be inherent in the argument, and that had been stated directly at one time in the paper read: namely, that a magma (as distinct from a replaced rock) tended rapidly to become "uniform." There were many references in literature to "uniform magma." Magmas were so large that laboratory observations in a beaker could be applied only with a certain amount of caution. Could Dr. Backlund, or any one present, tell them of an example where there was evidence that a large body of magma had been uniform or had had a tendency to become rapidly uniform?

DORIS L. REYNOLDS said that Professor Grout's remarks implied that the existence of large bodies of deep-seated granite magma was a proven fact. Had anyone seen such a magma? If not, by what criteria did Professor Grout distinguish the granites of magmatic origin to which he had referred? In his paper Professor Backlund in no way assumed the existence of granite magma, nor had she done so in presenting the paper for him.

A. HOLMES responded to Professor Grout's request for an example of a uniform magma by drawing attention to the fact that basaltic magmas often seemed to be of remarkably uniform composition throughout immense volumes. The results of chemical analyses which had been made from widely separated localities of the dolerites of the Whin sill and associated dikes of the North of England differed in no significant way from the average composition of the whole, determined by a composite analysis of thousands of specimens made by J. A. Smythe. In contrast, granite masses were rarely homogeneous, though megascopically some of them might appear to be so. Often, however, they showed conspicuous variations which persisted over large areas. The characteristic gradations from chemical heterogeneity to an approach towards homogenization suggested that granites had a quite different origin from the magmatic rocks of basaltic composition. He agreed, of course, that if magma of granitic composition had originated by rheomorphism it could not be expected to be chemically uniform from place to place, or to show the serial variations that should characterize a magma evolved by differentiation. But granitic magma formed by rheomorphism was a result of long-continued





FIG. 2.



FIG. 4.

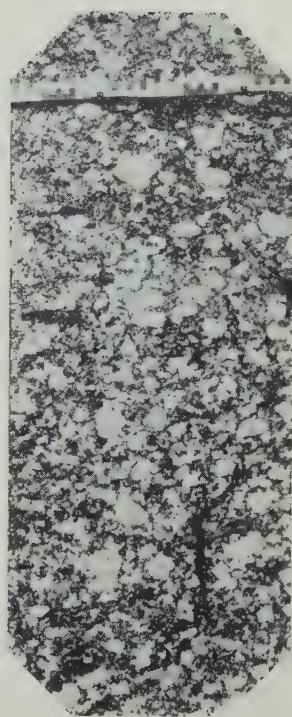


FIG. 6.



FIG. 1.

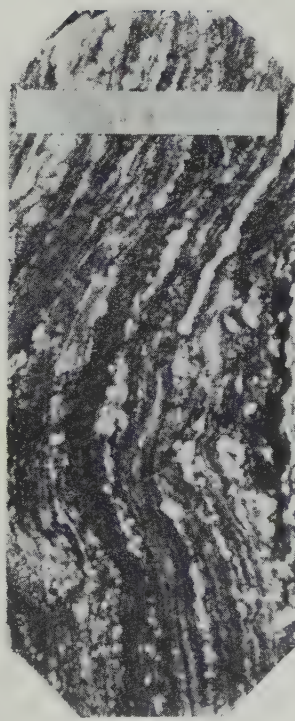


FIG. 3.

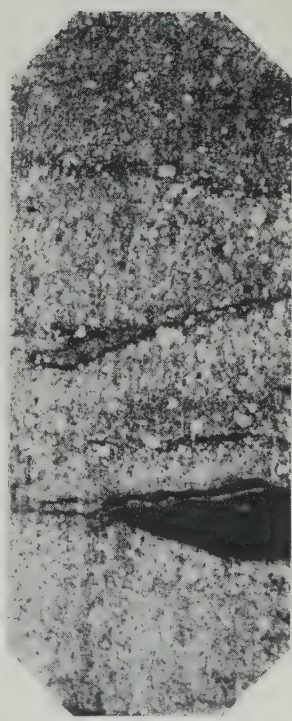


FIG. 5.





metasomatic processes and was not the cause of these processes. The fact that deep-seated basaltic magma—for the existence of which the evidence was good—failed to bring about petrological phenomena comparable to migmatization threw grave doubt on the view that ascribed the phenomena of granitization to the action of granitic magma.

MARGARET F. BOOS said that a comagmatic province composed chiefly of granitic rocks was exposed in the Front Range of Colorado and Wyoming, United States of America. There were three successive developments of Pre-Cambrian granites in an area about four hundred miles from north to south and up to one hundred miles wide from east to west.

The earliest granitic rocks had obviously been developed by metasomatic processes in country rock consisting of well stratified sandstones, shales, thin limestones, and intercalated basic lava flows. Cores of quartz-monzonite-porphyry and gneissic granite were enveloped in mica-schist, gneiss and skarn rocks.

The second generation of granite was chiefly of magmatic origin. It occurred chiefly in two large widely separated batholithic gneisses that had pushed up and aside the early monzonites, schists and gneisses. Typical granites of the second generation were much alike from place to place. Xenoliths of the early metasomatically developed "granites" were strewn about in the second generation masses.

The third and final stage of Pre-Cambrian magmatic activity in the Range produced a variety of large and small plutons in seven areas peripheral to the second generation batholiths. Mineralogically, petrographically, structurally, and in physical appearance the granites of the last generation were alike in all the plutons. Lineation, flow structures, stope-contacts and lit-par-lit injections into the already highly altered schists and gneisses indicated the true magmatic origin of the third generation granite. Minor minerals of the same species and frequency occurred in samples of granite from all bodies of the third development of granite.

D. R. BOWES said that differentiation, when operative, would produce a heterogeneous distribution of the rarer elements (see Wager, L. R. and Mitchell, R. L. "The distribution of Cr, V, Ni, Co and Cu during the fractional crystallization of a basic magma"—Section A). The well known association of certain of the rarer elements with basic rocks and others with acid rocks was evidence of this.

In reply to the discussion of his paper H. E. BACKLUND wrote as follows :

With regard to Dr. A. F. Buddington's query as to my interpretations of the origin of the major metallic constituents of the ore deposits, these are published in extenso in a memoir of 1943 (*Geol. Rundsch.*, 34) which is quoted by Dr. Reynolds in her paper on "The Association of Basic Fronts with Granitization" (*Science Progress*, 35, 1947). They were recapitulated by me in an address read before the Geological Society of Edinburgh in April, 1948, which is to be published shortly in English. An excellent exposé "On the Geochemistry of Swedish Iron Ores and Associated Rocks and their Formation" is given by Dr. S. Landergren (1948), in which he discusses the original sedimentary and "basic front" components of the ores and their geochemical discontinuities.

In reply to Dr. F. F. Grout, it is but an idle desire to wish to have seen every granitic area that may be discussed. After having traversed several thousand miles of granitic areas of various ages in different continents one becomes acquainted with their typical and critical appearances in the field, as was pointed out by Dr. H. H. Read in the course of the Ottawa discussion, and able to reconstruct the structural and regional details when hints of these are given. "Granitic magma" is a hypothetical construction and the term is used in the paper in accordance with the pretended "definition" that presents it as a homogeneous silicate melt or a crystal "porridge." An inhomogeneous mixture does not fall under the definition of "magma," and has tentatively been called "migma" by Reinhard. Migma is supposed to be a mixture either of "endogeneous differentiation products" and homogeneous "residual-magma," or of "exogeneous inclusions" and the same "magma." It will be observed that these explanations are again given in terms of assumptions. In order to establish the "residual-magma" part of the hypothetical "migma" as an important factor in granitic emplacement the Zürich School has created (*Schweiz. Min. Petr. Mitt.*, 1943, 1946) a lot of well-sounding terms such as *kyriosoma*, *stromatosoma*, etc., the meanings of which incorporate the hypothetical conception of "magma." My own starting point is not that of hypothetical "magma," but the pre-existing sedimentary pile with its determinable inhomogeneities which are reflected, after transformation, within the masses of the replacing rocks.

Dr. A. Holmes correctly draws attention to the homogeneity of basalts which represent the closest approach possible to real magma.

Dr. Margaret F. Boos, I regret to say, starts her remarks with a "*contradictio in adjecto*" : if the earliest granitic rocks of the Front Range of Colorado and Wyoming were obviously developed by metasomatic processes in country rock "sandstones, shales, thin limestones and intercalated lava flows," they cannot be spoken of as "comagmatic" with later granites, because at the time of their formation no corresponding magma existed, not even an imaginary one. The quartz-monzonite-porphyry "cores" with "gneiss and skarn rocks" show all the characteristics of replacements of "basic front" type that took place close to the present day surface of the earth.

In the case of the second generation of granite ("chiefly of magmatic origin") which occurs in two large and widely separated "batholithic" gneisses, if Dr. Boos would graciously compare the areal extent of the older rocks pushed aside by the "batholithic" intrusions with the areal magnitudes of the "batholiths" themselves she would soon discover the insignificance of this shouldering stress in comparison with the struggle for space that would have been occasioned by the forcible grand-scale intrusion imagined. It is a local rheomorphic manifestation to which Dr. Boos refers. Apart from these local effects there is probably some conformity between the tectonic attitude of the "batholithic" gneisses and their "xenolithic inclusions" of the early metasomatic granites on the one hand, and the general regional strike of

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the whole area of older metasomatic granite on the other hand, which would indicate a replacement action in spite of the " batholiths " being suspected of being *chiefly* magmatic. The likeness of the " second generation " granites from place to place to which Dr. Boos refers is due to their emplacement within an older granite area that had already gone through the first stage of rough homogenization by metasomatic action.

The third and latest group of small peripheral granitic plutons referred to by Dr. Boos develops all the peculiarities of emplacement such as " lineation, flow structures, stope contacts and lit-par-lit injections " that I have shown in the paper to be typical forerunners of a granitic emplacement by ionic diffusion (= granitization). It is perhaps of some interest to mention that in the peripheral parts (N, S, and W) of the Uppsala granite area, the discussion of which forms the second part of my paper, there also exist two groups of younger granitic emplacements, the Fellingsbro and the Stockholm granites, which differ from each other and from the principle Uppsala granite in composition, but the members of which are very much alike within each group. These later granites have not been considered in this paper. The analogy with the area discussed by Dr. Boos, however, suggests the guess that in the Front Range granites the amount of potash will steadily increase in conformity with the increasing youthfulness of the granites. It is perhaps a point of interest that whereas Dr. Boos finds the *older* granitic rocks in the Front Range of Colorado and Wyoming to be metasomatic, and the *youngest* granites to be of " true magmatic origin," in Sweden the Geological Survey reckons the *oldest* granite in the Uppsala district—the Uppsala granite—to be a product of true " magmatic " activity, and the *younger* Fellingsbro and Stockholm granites to be " migmatites."

I would recommend Mr. D. R. Bowes to scrutinize the excellent maps of the Kangerdlugssuag region of East Greenland by Wager and Deer (*Medd. om Grønland*, 105, No. 4, 1939) and of its wider environs (L. R. Wager, *Ibid.*, 134, No. 5, 1947) ; to compare them with the sketch map of the analogous areas of Werner Mts., E. Greenland (W. Bierther, *Ibid.*, 114, No. 3, 1941), and of Eastern Traill Island, E. Greenland (H. P. Schaub, *Ibid.*, 114, No. 1, 1938 ; *Ecl. Geol. Helv.*, 35, 1942), and then to draw his own independent conclusion as to whether the *differentiation* postulated by Wager, that he quotes, *has been operative or not*. If Mr. Bowes will also study the description and maps of the Iveland-Evje-No area (Barth, *Norges Geol. Undersök.*, No. 168a) he may perhaps gain some insight as to *why* the association he quotes is a well known one.



# TRANSFORMATIONS MÉTASOMATIQUES ET ANALYSE TECTONIQUE

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## ABSTRACT

La conception de la transformation des sédiments tire ses racines des études stratigraphiques et tectoniques. Il en est ainsi pour les terrains post-cambriens et pour les séries plus anciennes. En essayant d'établir une classification stratigraphique des terrains précambriens, J. J. Sederholm se trouva en face d'un noeud de problèmes qu'il ne réussit à dénouer qu'à l'aide des principes du métamorphisme développés auparavant par l'école française. Ces origines sont importantes pour la structure logique du transformisme et son évolution. Le développement de la chimie physique et l'application de ses règles aux problèmes des roches a limité le champ de vision de beaucoup de chercheurs en les orientant, dans un but unique, vers les explications chimico-physiques. Ces écoles s'inspirent, chacune à sa façon, des résultats de laboratoire, et aboutissent à des résultats très divergeants, ce qui est compréhensible, puisqu'il s'agit d'extrapolations parfois assez étendues. Le cadre des données stratigraphiques, tectoniques et cinématiques délimite le champ de dispersion des extrapolations. Les progrès de l'analyse tectonique permettent d'esquisser la structuration du cadre en montrant les phénomènes sous l'angle d'une tectonique géochimique.

## INTRODUCTION

L'ÉCOLE de Werner ne connaissait qu'une seule catégorie de roches, les sédiments, dont les couches étaient déposées les unes sur les autres au fond des mers. Hutton introduisit une nouvelle catégorie: les roches éruptives, résultat de la consolidation de masses ignées. L'argument fondamental de Hutton pour la nature endogène des roches éruptives était d'ordre *structural*: puisque les filons de basalte et les granites recoupaient les couches sédimentaires, leur mise en place devait être postérieure à la formation des roches encaissantes. On rencontre donc, déjà au commencement de la géologie moderne, trois complexes de questions *tectoniques* qui nous occupent encore aujourd'hui, à savoir: (a) l'analyse structurale, dans le cas des roches éruptives: la détermination de la forme, des espaces qu'elles remplissent et la relation de la forme avec l'ensemble des structures régionales et (b) l'analyse cinématique qui consiste, pour le cas des roches éruptives, dans l'étude des traces de mobilité et de vitesses différentielles des milieux en contact, et des variations de la mobilité dans le temps; (c) l'analyse chronologique: la division en phénomènes synchrones et métachrones, la détermination de leur place dans la série des phases régionales et dans l'échelle stratigraphique.

Ces problèmes ont été repris pendant ces dernières 150 années par chaque génération, chaque fois avec des méthodes et des techniques d'investigation différentes, de plus en plus spécialisées; l'histoire nous montre que, malgré cette diversité des moyens d'investigation, les interprétations gravitent autour de quelques *idées-types*. Le catalogue de celles-ci contient les possibilités de la pensée humaine de grouper les phénomènes en question; il permet aussi de reconnaître l'étendue des problèmes les plus discutés et de voir les ramifications des discussions; on y reconnaît, comme sur une carte, des parties très détaillées et d'autres montrant à peine le tracé des grandes lignes.

À côté des roches sédimentaires et ignées, on reconnut bientôt une troisième catégorie, celle des *roches transformées* (portant encore des traces de leur nature primitive). La mobilité des particules à l'état cristallisé, déjà connue par J. Davy, Gay-Lussac, Mitscherlich, Haidinger et d'autres, fut introduite dans les interprétations géologiques par Heinrich Steffen (1810), par Keferstein (1820) et

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Keilhau (1828\*); les études de ce dernier, professeur à l'université de Christiania (Oslo) aboutirent en 1836 (Keilhau, 1838) à une première synthèse où l'on trouve déjà un certain nombre de termes encore en usage aujourd'hui tels que: métamorphose, méasomatose, et au lieu de granitisation le mot granitification. Keilhau distingue entre la métamorphose et la méasomatose (p.e.p. 47); la dernière est une transformation par substitution de la substance (substantielle Forvandlinger) avec apport et départ de matériaux. Il affirme que le rôle du géologue est d'abord de *reconnaître* les phénomènes avant de les expliquer.†

Sa conception fondamentale, reprise par Durocher (1846) et les autres classiques de l'école française, n'a pas changé dans ses grandes lignes. Adaptée aux progrès des sciences chimiques, physiques, minéralogiques et cristallographiques, elle constitue actuellement un des importants chapitres de la pétrologie.

Les considérations structurales, l'étude des structures préexistantes sont donc à la base des recherches sur la méasomatose. Il importe de souligner cette origine afin de ne pas perdre de vue les grandes lignes de l'évolution. Pendant celle-ci, l'attention fut tantôt dirigée vers l'élément stable: la structure préexistante, tantôt vers les transformations chimiques et minéralogiques. Ces dernières étant plus accessibles aux interprétations dynamiques de la chimie physique moderne ont surtout joui de la faveur des chercheurs depuis un demi-siècle.

La connaissance des structures ne s'est pas développée avec le même rythme. Le développement de la tectonique moderne montrant la fonction et l'interdépendance des éléments structuraux depuis l'échelle microscopique jusqu'à celle des continents est relativement récent. Plusieurs de ses méthodes et techniques ont été créées dans des régions non métamorphiques. Il fallait les adapter aux terrains transformés et à leurs problèmes spéciaux. Il semble donc utile d'esquisser le joint de la pétrographie et de la tectonique, tel qu'il se présente actuellement, dans le domaine des roches de transformation.

#### CARACTÈRES DE L'ANALYSE TECTONIQUE

Les trois catégories de roches et les phénomènes qui leur donnent naissance ont un aspect assez différent, suivant qu'on les regarde du point de vue tectonique, ou du point de vue pétrographique. Ceci n'est pas seulement dû à une différence de méthode, mais surtout à ce que le point de vue est différent et avec cela la structure logique de la classification et de l'interprétation. Loin d'être un désavantage, cette circonstance a ceci d'heureux que les résultats obtenus par deux voies indépendantes peuvent être comparés, se compléter et servir à un contrôle réciproque. Il est nécessaire pour cela de connaître la structure logique des deux sciences. Comme un exposé plus complet dépasserait le cadre de cette communication, nous nous bornerons à caractériser brièvement quelques méthodes tectoniques employées dans les terrains cristallins; cet exposé, forcément schématisé, ne pourra pas remplacer une description plus détaillée donnée ailleurs.

Pendant une période plus ou moins longue, une multitude de théories tectoniques eurent la faveur du public. Leur évolution et leur succession diffèrent de celles des théories pétrographiques par des caractères essentiels. Plusieurs théories contribuèrent à développer nos moyens d'investigation, d'autres ne laissèrent de traces que dans quelques atavismes terminologiques. Plusieurs techniques de recherche se sont développées indépendamment des interprétations changeantes. On peut

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\* p. 134 : "... , dass nicht notwendigerweise eine von den, wenigstens bis jetzt bekannten, Aggregationsformen, worin sich die Körper im flüssigen Zustande befinden, einer jeden Bildung oder Umbildung der festen Körper vorangehen müsse, sondern, dass im Gegenteil die starre Form die Bewegungen der Stoffe nicht ausschliesse," p. 134-135 : "Es kann und muss die Voraussetzung weggeräumt werden, dass die Teile der Gebirgsmassen, hinsichtlich ihrer specifischen Beschaffenheit und dem Orte, den sie jetzt einnehmen, überall noch immer dieselben sind, wie im Augenblick, wo sie oder ihr Material einst aus gasförmigen oder feurigflüssigem Zustande, oder aus einer Auflösung in irgend einem neptunischen Fluidum hervorgingen." On ne saurait mieux définir le principe des roches transformées.

† p. 47 : "... det er ikke Geologens Sag at forklare disse Processer ; han har for Tiden alene at erkjende dem som virkelig eksisterende."



distinguer nettement une tendance générale vers les méthodes de l'analyse géométrique, cinématique et chronologique.

Sur le plan pétrographique, on tend de plus en plus vers l'application des règles de la chimie, de la physique et de la cristallographie; il en résulte une image dynamique basée sur la thermodynamique et d'autres théories permettant un bilan des énergies en jeu. Cette tendance suppose l'existence de systèmes fermés et d'autres conditions, généralement non réalisées dans l'écorce terrestre. Pour jouir des avantages d'un système fermé, il est nécessaire de se servir de l'expérience qui permet d'obtenir parfois des produits analogues à ceux de la nature. Encore faudrait-il, pour tirer des conclusions d'une expérience, démontrer la *similitude exacte* (géométrique, cinématique et dynamique) du modèle réduit, ce qui serait parfois difficile, vu que certains facteurs ne peuvent être agrandis ou réduits à volonté. Dans d'autres cas, on met à contribution des artifices souvent très ingénieux, p.e. en *supposant* un système fermé et en imaginant, par déduction, ce qui s'y passerait.

Le célèbre physicien écossais J. C. Maxwell a montré dans la seconde moitié du siècle passé la différence fondamentale entre un système fermé et un système non fermé. En adaptant les notions de Maxwell à notre problème, on pourrait résumer cette note de la façon suivante: *la pétrographie actuelle semble avoir dans beaucoup de ses branches la tendance à opérer avec des systèmes fermés, tandis que les meilleures méthodes de la tectonique sont conçues pour explorer des systèmes non fermés*. Les possibilités de la tectonique sont, de ce fait, limitées et sa structure logique en porte la marque.

Considérons le rôle des trois catégories historiques de roches sur le plan tectonique: les observations concernant leur forme, leur assemblage dans l'espace, leur structure interne dans les différents ordres de grandeur peuvent nous donner des renseignements sur les mouvements, les mobilités relatives et la succession des mouvements.

La plus grande partie des observations ne nous donne que des dimensions et des directions, le plus souvent mesurées par rapport aux coordonnées géodésiques; la définition des mouvements se rapporte donc le plus souvent à des systèmes de référence locaux ou régionaux, provisoirement reliés.

Comme les autres sciences, la tectonique suit les principes de Descartes; elle divise les difficultés pour les vaincre. Pour classer les structures, elle en étudie, aussi soigneusement que possible, les relations spatiales. Elle les subdivise suivant leur forme et les répartit dans différents ordres de grandeur. Les éléments des ordres inférieurs remplissent ceux des ordres supérieurs. Les structures de grandeur différente se ressemblent dans certains cas; mais, le plus souvent, *il n'y a pas similitude*. On ne peut donc pas généraliser de bas en haut ou inversement. Cette règle n'est malheureusement pas souvent observée, ce qui mène parfois à des extrapolations assez baroques.

Puisqu'il n'y a pas similitude générale pour tous les ordres de grandeur, la plupart des objets tectoniques ont leurs dimensions caractéristiques, d'ailleurs assez variables, qui leur sont propres et en dehors desquelles on ne les trouve pas dans la nature (cf. Wegmann, 1947, p. 225-226). Ces caractères donnent lieu à une classification dimensionnelle qui permet de considérer l'assemblage des objets tectoniques en organes dont les parties ne fonctionnent que dans le cadre de l'ensemble. Les objets ou organes ne sont pas des systèmes fermés; ils font partie d'ensembles plus grands. La classification dimensionnelle permettra un jour d'introduire dans la tectonique des considérations dynamiques en se servant de l'analyse dimensionnelle.

La prudence conseille d'analyser chaque ordre de grandeur par des méthodes appropriées, ce qui permet de contrôler les résultats par des recoupements depuis le bas et depuis le haut. Ce sont aussi des raisons pratiques qui poussent à diviser l'analyse en différents ordres de grandeur; les techniques à l'échelle des cartes régionales et à l'échelle microscopique sont très différentes. Comme beaucoup de chercheurs ne sont familiarisés qu'avec un certain nombre de techniques, le travail en équipe est désirable; on évite ainsi les extrapolations excessives souvent dues à l'insuffisance des connaissances techniques.

Les techniques peuvent être groupées en trois séries de méthodes principales: (1) l'étude des formes et leurs relations dans l'espace, l'analyse structurale; (2) l'analyse chronologique et cinématique; (3) la tectonique comparée.

La majeure partie des structures observées est le résultat d'un grand nombre de mouvements, dont il s'agit de relier les traces en groupes synchrones et métachrones, ce qui permet de reconstruire une série d'images dans l'espace, échelonnées dans le temps. Les coupures de ce temps varient probablement d'une façon discontinue dans la plupart des cas, puisqu'elles ne sont déterminées que par des événements qui ont laissé des traces; on ne peut pas s'attendre à ce que ces événements se suivent avec la régularité d'une montre. Les phénomènes isolés ne sont d'aucune aide; les méthodes permettant de relier les traces de mouvements sont donc particulièrement importantes.

Les séries d'images ne montrent que des déplacements et des transports, mais pas de forces, d'énergies, de poussées, pressions et autres notions de l'arsenal des théories géologiques du passé. Ce manque de caractère dynamique les rend moins "pédagogiques" et moins spectaculaires, fait qui s'explique par l'amour atavique des humains pour la force et la puissance. Les séries d'images correspondent à celles d'un film qui ne montre que la succession des images. C'est à cause de l'interprétation instantanée et inconsciente que le spectateur croit voir un jeu de forces. Une grande partie des interprétations dynamiques en pétrographie et en tectonique ne sont que des interprétations inconscientes, souvent difficiles à éliminer.

Les coordonnées fournies par les images dans le temps et dans l'espace limitent singulièrement l'extension, le déploiement des théories dynamiques avec leurs prétentions universalistes. Elles fournissent par contre des cadres à l'application rationnelle des règles de la chimie et de la physique.

Après cette introduction forcément un peu abstraite, passons à un autre point où les études sur la métasomatose et la tectonique s'entreprennent. C'est une image créée pendant un siècle par de nombreuses générations de géologues.

#### NIVEAUX DE TRANSFORMATION ET D'INTRUSION

À la fin du 18<sup>e</sup> siècle, on reconnut que les massifs granitiques montraient tantôt des contacts francs, tantôt des passages ménagés aux roches encaissantes. Les neptunistes et les plutonistes interprétèrent ce fait à leur manière. Le célèbre géologue norvégien Keilhau considéra les passages comme une métasomatose (il a employé ce mot) et créa le terme de "granitification" (1836).

L'école française distingua un terme moins évolué, la feldspathisation. Elle sépara tôt l'action métasomatique de l'intrusion (Durocher, 1846; Virlet, 1846), la fixation d'un fluide mobile par une trame stable (Durocher, 1846, p. 557) du déplacement massif des matériaux mobiles entre les épontes plus ou moins solides. Ces masses pouvaient être fondues ou formées par des amas cristallisés mobiles (à la manière des glaciers). Delesse (1861, p. 547) résume ces observations de la façon suivante: "Les roches stratifiées peuvent se changer en roches métamorphiques, et, lorsque le métamorphisme est très énergique, elles passent même aux roches plutoniques les mieux caractérisées. Ainsi, par exemple, dans les roches à base d'orthose, le gneiss passe insensiblement au granite, et dans les roches à base d'anorthose, le schiste hornblendé passe à la diorite. Les roches plutoniques se sont donc formées aux dépens des roches métamorphiques; elles représentent le terme extrême du métamorphisme général; elles sont l'effet et non la cause de ce métamorphisme."

Cette synthèse fut confirmée par une multitude d'observations, accumulées pendant presque un siècle, dans les sections pratiquées par la nature à tous les niveaux des chaînes précambriennes et postcambriennes. Elle permet de distinguer deux étages dans un segment de l'écorce terrestre:

(a) celui de la formation des roches plutoniques par transformation, (b) celui de l'intrusion plutonique et parfois de l'extrusion.

Ces deux étages sont reliés par des passages. Leur profondeur n'est pas fixe, mais varie pour un segment donné dans l'espace et dans le temps. C'est un des problèmes les plus saisissants de la tectonique moderne de suivre le déplacement de ces étages à l'intérieur de l'écorce terrestre.

Notre niveau d'observation est déterminé par la topographie actuelle; celle-ci recoupe dans une région donnée les traces de ces étages à plusieurs moments consécutifs de l'histoire. C'est ainsi qu'on distingue dans beaucoup de chaînes de montagne, surtout dans les segments précambriens et calédoniens, profondément découpés: les granites avant-coureurs, arrivés d'un étage inférieur situé à ce



moment au-dessous du niveau d'observation; les granites principaux, quand l'étage inférieur est remonté jusqu'au niveau d'observation; c'est à ce stade que les transformations sont le plus visibles; les granites tardifs, quand la zone de transformation s'est retirée vers les profondeurs et envoie ses derniers messages jusque dans la zone de la topographie actuelle (cf. Wegmann, 1930, fig. 3, p. 71 et 1935, p. 335).

On constate donc un mouvement relatif des étages de transformation et d'intrusion par rapport au niveau d'observation. La profondeur de celui-ci par rapport aux anciennes surfaces topographiques doit être déterminée par d'autres méthodes.

Les phénomènes de la transformation et de l'intrusion ont été arrêtés à tous les stades de leur évolution, de sorte que l'anatomie comparée des formes et de leur structure interne est possible. Les faciès des séries dans leurs différents étages sont caractéristiques. J. J. Sederholm les a décrits, photographiés et dessinés; ses nombreux travaux fournissent une précieuse documentation.

Les trois catégories de roches granitiques se distinguent au point de vue *structural*: les massifs du premier groupe sont déformés par des failles, des plis, des charriages, des laminages, etc.; les massifs du second groupe se substituent aux roches préexistantes tout en laissant souvent intactes les grandes lignes de la structure antérieure qui peut être suivie à travers les "taches granitiques" de ce genre. L'importance de ce phénomène, longtemps mis en doute ou amoindri par les partisans de la formation des grands massifs granitiques par différenciation et leur mise en place par des mouvements en masse, a été reconnue dernièrement par Bowen (1947); sa théorie n'a pas encore réussi à en donner une explication satisfaisante. Dans certains cas, la structure prégranitique est conservée à l'intérieur de l'espace granitisé, tandis qu'elle a évolué dans les régions non granitisées. Les intrusions du dernier groupe suivent des plans de séparation de la masse rocheuse (diaclasses, fentes, failles etc.) au-dessus de la zone principale de transformation. Le réseau de ces remplissages tardifs fixe l'image des conditions d'anisotropie de l'étage supérieur à la fin de la période des apports endogènes.

Les produits de la métasomatose nous aident à reconstruire la "tectonique en mouvement" à l'intérieur d'un segment donné. Ce procédé peut être comparé à certaines techniques modernes pour obtenir des préparations histologiques; en imprégnant les tissus ou en remplissant les interstices, on peut obtenir, soit l'image de la structure interne, soit un moulage, p.e. d'un réseau de fentes. La métasomatose fixe dans beaucoup de cas des images structurales des différents ordres de grandeur qu'il s'agit d'étudier par des techniques appropriées et de placer dans la série chronologique d'ordre local et régional.

Cette chronologie des événements profonds ne peut être fixée généralement que d'une façon approximative dans l'échelle stratigraphique; il est parfois possible d'en préciser la position par la méthode de la "synchronisation verticale" (Wegmann, 1947, p. 233).

A ces notions tectoniques correspond sur le plan pétrologique la distinction entre les substances se déplaçant à travers une roche plus ou moins solide et réagissant avec elle d'une part, et, d'autre part, les roches résultant de la solidification finale d'une masse s'écoulant entre des épontes. Il sera donc nécessaire de distinguer entre la roche-hôte, les substances d'apport et de départ, la roche mixte ou migmatite, ou, dans le cas de la formation de masses d'écoulement (plutoniques, subvolcaniques ou volcaniques): la composition de cette masse, souvent appelée le magma, qui se sépare à son tour en plusieurs fractions lors de sa solidification: la roche et les composants mobiles (volatils) pouvant se fixer à leur tour en donnant lieu à des phénomènes de métasomatose d'une autre génération. Ces notions, créées en partie par les géologues français, il y a un siècle, parfois en des termes un peu variables, permettent encore aujourd'hui de placer les descriptions pétrographiques dans le cadre de l'évolution tectonique. Même Rosenbusch semble faire la différence entre la composition des magmes et des roches puisqu'il affirme que le domaine de la pétrographie est la partie *solide* de l'écorce terrestre et qu'elle ne s'occupe des magmes que pour autant qu'ils donnent naissance à des roches éruptives. Il était réservé à une école moderne de créer une confusion fatale en désignant du nom "type de magmes" des analyses de *roches* et de se baser sur cette erreur pour ériger tout un système.

L'analyse cinématique de l'étage inférieur permet de distinguer deux catégories de phénomènes qui interfèrent d'une façon complexe :

(1) le déplacement des fronts de transformation

(2) le transport des masses avec leurs structures qui se déforment en partie au cours du déplacement.

Ad (1) Les phénomènes d'un front de transformation sont complexes puisque nous avons (a) une structure ou trame restée reconnaissable malgré les transformations subies par les substitutions chimiques; (b) des éléments qui s'y fixent; (c) des éléments qui en partent et (d) des éléments qui traversent l'espace en question. Le tracé actuel d'un front (p.e. sur une carte géologique) est la position extrême que le front en question a atteint.

Pour reconstruire dans l'espace la forme des différents fronts, il est nécessaire d'en connaître la succession; la connaissance de celle-ci est aussi importante que celle de la stratigraphie pour beaucoup de problèmes structuraux. Les études de Reynolds (1946) sur l'échelonnement des fronts sont de la plus haute importance pour en saisir la forme et en reconstruire les mouvements. Comment peut-on fixer chronologiquement l'avancement des fronts dans une série? Trois méthodes se présentent: l'âge est fixé: (a) par le terrain le plus jeune atteint par le front et, d'autre part, par le terrain le plus ancien contenant des galets ou recouvrant en discordance les roches transformées; (b) par rapport à des déformations qui peuvent être suivies et datées dans un niveau supérieur; (c) par des filons basiques traversant la masse rocheuse avant ou après le passage des fronts. Ces filons basiques représentent souvent les indicateurs les plus sensibles et sont précieux parce que certains montent dans les régions superficielles formant parfois des filons-couches ou même des appareils volcaniques dans les terrains sédimentaires et permettent ainsi de placer les phénomènes dans l'échelle stratigraphique. De nombreuses roches décrites sous le nom de lamprophyres ne sont autre chose que des filons basiques transformés.\*

Ad (2) L'étude des traces des déplacements de masses couvre tout le champ des méthodes et techniques de l'analyse structurale. Elle comprend tous les ordres de grandeur depuis ceux des zones orogéniques jusqu'à l'étude microscopique. Elle comprend aussi bien les plis et charriages, les failles et diaclases que les intrusions et extrusions des masses rhéomorphiques (Backlund, 1937) composées par des silicates, les phénomènes des mouvements salifères et les déplacements donnant lieu à des volcans de boue, pour autant qu'il est possible de reconstruire leur forme, leur structure interne et le mouvement des parties par rapport à une système de référence.

Les recherches structurales se poursuivent à toutes les échelles de grandeur. Comme les techniques appliquées aux différents ordres de grandeur ne sont pas identiques, les résultats obtenus ne dépendent pas directement les uns des autres. Il est donc possible de contrôler un échelon par l'autre (cf. Wegmann, 1947, p. 226). Il est nécessaire de souligner cette possibilité de contrôle parce qu'elle permet de réduire les extrapolations à un minimum. Quand on voit dans plusieurs travaux modernes des extrapolations de 1 : 100,000, on peut devenir sceptique à l'égard de certains travaux tectoniques.

Trois espèces de surfaces nous permettent par leurs intersections de reconstruire l'image structurale: (1) la surface topographique actuelle ou surface d'observation ou de référence; (2) les surfaces de références anciennes aujourd'hui déformées (surfaces de stratifications, pénéplaines, filons, parfois aussi d'anciennes structures plus compliquées d'un stade antérieur définissable) dont la position actuelle permet de reconstruire le mouvement ou transport des masses; (3) les fronts de transformation traversant les structures de la deuxième catégorie.

Le tracé et la nature des intersections permettent de déterminer la profondeur relative de nombreux phénomènes observés et de les placer dans les images à trois dimensions.

\* Il est parfois difficile de les distinguer d'une autre espèce de roche à caractère lamprophyrique qui prend naissance lors de la montée d'une roche basique dans une faille; les brèches de dislocation de nature granitique peuvent être assimilées en plus ou moins grande quantité et changer le caractère de la roche (cf. Wegmann, 1938, Fig. 42, p. 87). Les différents cas se distinguent par leur milieu géologique. Leur composition minéralogique peut montrer des types de convergence.



Il est clair qu'une image essentiellement géométrique et cinématique contiendra un certain nombre de traits difficilement explicables par les théories dynamiques actuelles. Leur explication sera rendue possible, soit par le développement de la chimie et de la physique, soit par la division judicieuse en opérations partielles plus simples.

#### LES CONTRIBUTIONS DE LA GÉOCHIMIE

L'image obtenue par l'analyse tectonique doit être soumise à un contrôle par des recherches conduites d'une façon indépendante, mais à son tour adaptée à l'exploration de systèmes non fermés. Les investigations de V. M. Goldschmidt (1928, 1932) et de son école remplissent en une large mesure ces conditions; elles mènent à la reconstruction des cycles montrant le passage d'un milieu à l'autre. Les milieux sont caractérisés par les proportions des composants, donc par des valeurs sans dimensions. La seule donnée spatiale des diagrammes est la profondeur relative par rapport à la surface de la terre.

Les études récentes très approfondies de Sture Landergren (1948) sur la géochimie des gisements de fer de Suède reproduisent d'une façon étonnante l'image résultant de la tectonique. Les études sur les cycles d'autres éléments, comme ceux de Landergren (1945) sur le bor, de Barth (1947) sur le fluor, de Rankama (1944) sur le tantalum et beaucoup d'autres relient les roches d'une certaine profondeur avec celles de la surface et confirment les cycles prévus par l'analyse tectonique.

A part une vague indication des profondeurs, les diagrammes des cycles géochimiques ne donnent pas de coordonnées, ni de l'espace, ni du temps. Un premier pas vers une représentation spatiale a été fait par V. M. Goldschmidt (1928) comme résultat de ses études sur la géochimie de l'oxygène. Ses considérations furent reprises par Brajnikov (1945) et par Barth (1948, a, b,); ce dernier en a déduit un nouveau procédé de statistique pétrographique qui est un grand progrès par rapport aux méthodes d'Osann, de Becke et aux imitations plus ou moins perfectionnées; ce progrès est comparable, dans le domaine de la minéralogie, au passage des formules chimiques classiques aux représentations des réseaux cristallins. Nous voyons là de grandes possibilités pour l'avenir.

La géochimie évoluera certainement en profondeur par des méthodes de plus en plus raffinées; elle ne pourra élargir son champ qu'en fixant ses milieux et assemblages par rapport à des coordonnées de l'espace et du temps, construisant de cette façon un pont vers le domaine de la tectonique. D'autre part, de nombreux chemins se dirigent depuis la tectonique à la géochimie; nous les exposerons ailleurs. De cette façon, une géochimie tectonique d'une part, et une tectonique géochimique d'autre part prennent naissance. Les travaux d'approche de part et d'autre sont nombreux. Puissent-ils se rejoindre un jour!

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### DISCUSSION

A. DEMAY: Le Professeur Demay est bien d'accord avec le Professeur Wegmann sur le fait que nous ne pouvons pas, dans l'étude des phénomènes de la tectonique profonde, dépasser le point de vue cinématique et définir les forces qui provoquent les mouvements.

Il signale pourtant qu'à défaut de définition des forces, certaines relations peuvent parfois être établies. L'ensemble de ses observations dans le Massif Central permet d'affirmer que les forces orogéniques en jeu dans la zone profonde étaient, au moins pour la part essentielle, de même nature et de même orientation que dans la zone supérieure, où la tectonique est normale, par exemple de style pennin. Ceci ne peut être établi que dans les régions où l'on observe le passage d'une tectonique normale à une tectonique profonde.

Le Professeur Demay signale, d'autre part, qu'il utilise le terme de granite intrusif par opposition au granite profond, dans un sens large, assez différent de celui adopté par le Professeur Wegmann. Ce dernier sens semble correspondre aux granites diapires, définis par le Professeur Cloos et dont le déplacement par rapport aux roches encaissantes apparaît clairement.

Enfin le Professeur Demay est entièrement d'accord avec le Professeur Wegmann sur la nécessité d'étudier, dans un complexe cristallophyllien et cristallin, l'évolution orogénique en même temps que les caractères lithologiques ou purement magmatiques. Les méthodes uniquement lithologiques et statiques, utilisées parfois encore aujourd'hui, conduisent à une interprétation très incomplète des phénomènes et même à des erreurs.

E. WEGMANN répondit: M. Wegmann est d'accord sur le troisième point. Quant au terme 'intrusion' on l'emploie d'une façon différente dans différents pays: on peut se tenir à une terminologie consacrée par la tradition, ou alors on peut l'adapter aux connaissances actuelles. Intrusion veut dire mouvement en masse et on peut trouver les traces à l'intérieur ou à l'extérieur des massifs. Le premier point, la nature des forces reste probablement énigmatique, puisqu'on ne connaît pas les forces qui ont donné naissance aux plissements, ni celles qui ont donné naissance aux structures profondes.



# THERMODYNAMIQUE DE LA PETROGÉNÈSE PROFONDE (MÉTAMORPHISME ET VOLCANISME)

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## ABSTRACT

L'auteur étudie le mécanisme possible des échanges intra-crustaux à l'échelle de la molécule. Il fait intervenir les phénomènes de diffusion et les variations d'énergie interne se produisant lors des changements polymorphiques. Il définit ainsi des états oligophasés hyper-diffusifs qui sont les conséquences directes ou indirectes des phénomènes liminaires décrits dans une autre note (section M).

Cette théorie constitue une explication géophysique des phénomènes de granitisation et de migmatisation décrits par Sederholm, Wegmann et Backlund, ainsi que des "fronts" de Doris Reynolds.

## I. IMPORTANCE DES ÉTATS DE DÉSORDRE OLIGOPHASÉ

DE nombreuses théories ont été proposées sur le métamorphisme et l'évolution des magmas. Toutes ces théories admettaient généralement, comme postulat, que le phénomène physique invoqué, unique et homogène, reste constant, ou varie d'une façon linéaire, en fonction de la profondeur.

Plus récemment, Ramberg [14] a calculé, par les méthodes de la thermo-dynamique, la répartition des éléments mobiles en fonction de la pression. Pour cela, il considère comme fixes, certains éléments composant la trame. Barth pose comme postulat que la trame était constituée par un réseau d'oxygène au milieu duquel circulent des cathions.

Ces derniers travaux constituent un progrès considérable; mais les résultats calculés correspondent à des conditions d'équilibre idéales, difficilement atteintes. Il est, de plus, nécessaire de tenir compte de deux phénomènes importants pour la Pétrogénèse profonde.

(a) Au-dessous d'un certain seuil P.T.X. (pression, température, concentration), l'équilibre prévu par la thermodynamique classique ne peut être réalisé, la matière restant en état de faux équilibre. L'augmentation de la viscosité avec la pression peut provoquer un retard considérable, et même un arrêt dans le retour à l'équilibre.

(b) Chaque fois que la matière présente un changement allotropique, on a constaté expérimentalement que son activité chimique et son pouvoir de diffusion, étaient augmentés dans de fortes proportions. Les états naissants et les états de tension dirigés (shearing stress) conduisent à des résultats analogues. Le milieu est *réactivé* à l'intérieur de la zone de transformation allotropique. Pour un faible intervalle de température et de pression, certaines propriétés, comme la diffusion, peuvent ainsi devenir 3,000 fois plus importantes. A 573°, une variation de quelques degrés transforme le quartz  $\alpha$  en quartz  $\beta$ . De même d'importantes transformations allotropiques se produisent pour de faibles augmentations de pression.

Même pour un cristal idéalement parfait, on passe ainsi brusquement de l'ordre cristallin à un état de désordre. Pendant la phase de désordre, au-dessus et au-dessous de la température de transformation, l'énergie potentielle du réseau est minimum pour l'état initial et l'état final; elle passe par un maximum entre les deux états (Figs. 1 et 2).

Dans cet "état de désordre," la matière n'est, ni cristallisée, ni liquide, ni gazeuse, dans le sens attribué à ces mots à échelle humaine. Afin d'éviter des analogies, entachées d'anthropocentrisme, nous avons nommé [8] état oligophasé tout état de désordre statistique rendant l'ensemble du milieu diffusible et réactionnel, quelles que soient les causes qui provoquent cet état.

En outre, à partir d'une certaine pression, un deuxième phénomène s'ajoute aux changements

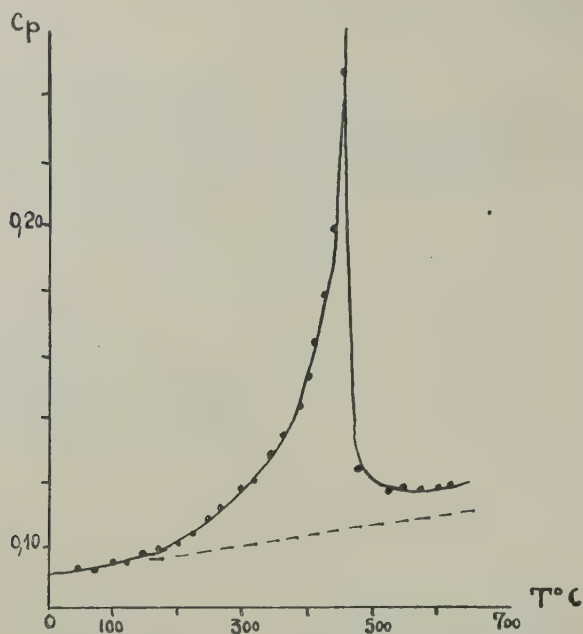


FIG. 1.—Variations de la chaleur spécifique au passage de l'état ordre—désordre par changement de structure d'un alliage métallique.

En ordonnées : la chaleur spécifique ; en abscisses : la température (d'après Moser).

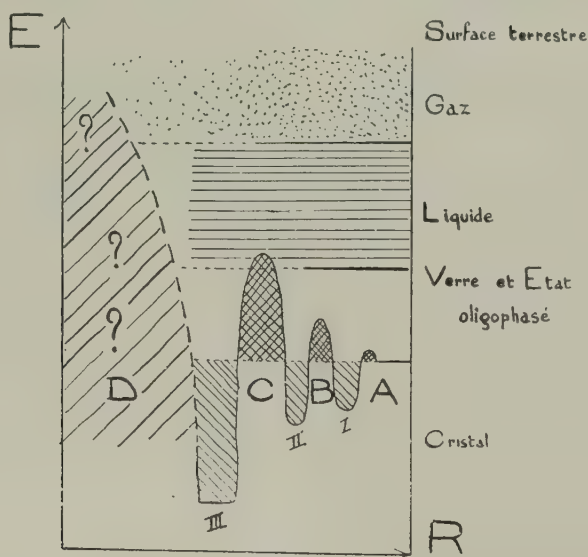


FIG. 2.—Schéma montrant les différents états de la matière en fonction de l'énergie potentielle électronique et de la distance interatomique.

En ordonnées : l'énergie du système ; en abscisses : la " fonction de configuration " qui dépend de la distance interatomique. (Ce schéma est destiné à montrer les relations entre les différents états, depuis les conditions de la surface terrestre (à droite A), jusqu'au noyau terrestre (à gauche D). En augmentant la pression (de droite à gauche), on passe successivement par des états allotropiques I, II, III, séparés par des phases oligophasées A, B, C (quadrillés). Au-delà de l'état III, les orbites électroniques extérieurs sont fortement perturbés et on passe dans un état spécial qui est celui du noyau terrestre (D).



allotropique; les champs interfaciaux sont renversés (anamigmatisme). Dans les expériences de laboratoire, la durée des états oligophasés est extrêmement courte et par suite leurs effets sont limités. Au contraire, dans les processus géologiques, les cristaux peuvent rester à l'intérieur de la zone de transformation pendant des temps très longs. La prolongation de l'état de désordre correspondant, produit des transformations qui seraient négligeables dans les expériences de laboratoire. Au cours d'une durée géologique, la diffusion provenant des cristaux à l'état de désordre s'étendra à une distance plus ou moins grande de ceux-ci. Un phénomène d'autocatalyse peut s'amorcer. La variation brusque, due à ces phénomènes, est indiquée sur la Fig. 3 entre les profondeurs B et C.

Les données expérimentales modernes sur les éléments formant les roches sont encore insuffisantes pour permettre de définir, rigoureusement, les profondeurs auxquelles se passent de tels phénomènes. Néanmoins, on peut établir leur ordre de grandeur.

La transformation du quartz  $\alpha$  en  $\beta$ , à  $573^\circ$ , correspond à une profondeur de 20 à 25 kms. environ. Pour une pression de 2,500 à 4,500 kg. cm.<sup>2</sup> (10 à 15 kms.) un certain nombre de substances artificielles, telles que  $A_3I$  et  $ClO_4C_3$ , subissent des transformations polymorphiques nettes.

Pour des pressions beaucoup moins élevées de 150 kg./cm.<sup>2</sup>, Wyart a mis en évidence des transformations de silice vitreuse en cristobalite et de cristobalite en quartz, en présence de vapeur d'eau potassique à  $340^\circ$ , ce qui correspond à des profondeurs de 12 kms. Sous 2,400 kg./cm.<sup>2</sup> (10 kms.), on observe une diminution de la tension interfaciale au contact eau-mercure. Le nombre considérable des constituants intervenant dans l'écorce terrestre facilitera de telles transformations, et les états de désordre correspondants. Il est donc légitime de supposer que les *suractivations* dues aux transformations allotropiques, aux renversements des tensions interfaciales, à la pression d'eau supercritique, jouent un rôle important à des profondeurs où les géologues situent les phénomènes de pétrogénèse profonde (migmatisation, granitisation, différenciation regionales).

Avant de discuter les théories pétrogénétiques, il est donc nécessaire de déterminer les pressions et températures, dans l'intervalle desquelles les phénomènes physiques peuvent agir géologiquement.

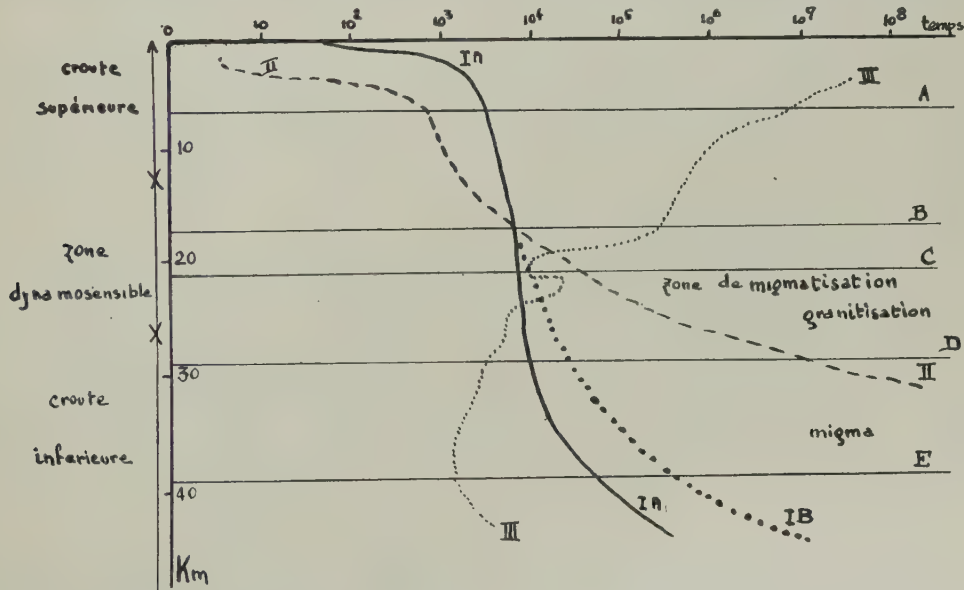


FIG. 3.—Variations en fonction de la profondeur de la durée de différents phénomènes, pour une intrusion sous 1 m. d'épaisseur.

En ordonnées : les profondeurs ; en abscisses : les temps, en années. Courbe I, temps de cristallisation total de l'intrusion. Courbe II, durée de la chute d'une particule de 5 cm. de rayon traversant les 20 m. d'épaisseur de l'intrusion. Courbe III, durée de diffusion nécessaire pour que les ions provenant de la paroi amènent à un état d'équilibre homogène la totalité de l'intrusion.

### PART III : METASOMATIC PROCESSES IN METAMORPHISM

#### II. ANALYSES DIMENSIONNELLES DES PHÉNOMÈNES INTRACRUSTAUX

Nous avons essayé dans la figure, ci-jointe (Fig. 3), de définir le rôle de trois sortes de phénomènes pouvant intervenir dans la pétrogénèse.

(a) La vitesse de chute en fonction de la profondeur des cristaux dans un magma fluide tel que le prévoit la théorie de la cristallisation-différenciation (Bowen, Niggli).

(b) La vitesse de diffusion en fonction de la profondeur.

(c) La vitesse de refroidissement des intrusions.

Les données expérimentales certaines que nous possédons actuellement pour établir de telles courbes sont encore peu nombreuses; aussi la figure 3 s'appuie autant sur les résultats géologiques que sur les données de la physique. Les courbes en question ont été établies pour une intrusion ayant 20 m. d'épaisseur et offrant en surface, une différence de température de 800° avec milieu ambiant. Les abscisses représentant les temps en années (échelle logarithmique) et les ordonnées les profondeurs. La courbe I donne la durée de la cristallisation complète de cette intrusion en fonction de la profondeur. La courbe II, donne le temps qu'un cristal de 5 cm. de rayon mettrait pour traverser les 20 m. d'épaisseur de l'intrusion, sous l'action de son propre poids. La courbe III indique la durée nécessaire pour que la diffusion des atomes provenant des parois produise une homogénéisation complète sur les 20 m. d'intrusion et un état d'équilibre par rapport au milieu ambiant.

Dans la partie supérieure de la croûte terrestre, la vitesse de chute des particules dans un magma immobile en cours de refroidissement, peut théoriquement être assez grande pour qu'il se produise, avant le refroidissement total, une différenciation sur l'épaisseur de 20 m. Toutefois cette chute est ralentie ou arrêtée si le milieu présente des courants de convection comme cela est probable. Au-delà d'une certaine profondeur que nous fixons pour le moment entre 8 et 12 kms., la vitesse de chute semble insuffisante pour amener une différenciation sur la hauteur d'une petite intrusion (20 m.).

Dans cette partie supérieure de la croûte, les phénomènes de diffusion à l'état solide assez lents, produisent seulement des transformations au contact entre les différents minéraux (réactions rims) où sur les bords immédiats de l'intrusion (0 m, 50 à 3 m. au Djebel Arroudjaoud).

Au-dessous de la profondeur B (croûte supérieure), la vitesse de diffusion augmente brusquement par suite des phénomènes producteurs de désordre invoqués précédemment. C'est la zone dynamo-sensible (D.S.). A cette profondeur, la totalité de l'intrusion peut être transformée par diffusion avant la fin de sa cristallisation si le processus de cristallisation est normal, le refroidissement suit la courbe IA; mais si l'on tient compte du ralentissement dû aux transformations allotropiques, on doit admettre la possibilité d'une courbe de solidification IB.

Ce schéma montre l'influence de la pression dans ces phénomènes de transformation profonde. L'influence du temps est non moins appréciable. Si le phénomène dure 10<sup>6</sup> années, la diffusion devient, au-delà de 15 kms. de profondeur, le phénomène dominant, agissant sur de grandes masses. On y voit nettement que les grandes évolutions pétrographiques régionales peuvent être dues à la diffusion suivant un mécanisme qui sera précisé plus loin. Ainsi se formeront les provinces pétrographiques et les séquences des roches éruptives. Le métamorphisme général, la granitisation se produisent de même, dans la zone où la diffusion est le phénomène dominant. Les phénomènes de pétrogénèse peuvent donc avoir des mécanismes différents suivant les échelles de temps et d'espace.

#### III. ÉQUILIBRE CORTICAL ET MÉTAMORPHISME GÉNÉRAL

Dans une écorce où interviennent seulement des gradients de pressions, sans transformation allotropique ni apport extérieur, les calculs de Ramberg [14] et de Barth [3] précisent l'état d'équilibre final obtenu par une évolution lente et réversible. Par contre, s'il apparaît, en un point quelconque de l'écorce des perturbations d'origine soit interne, soit externe, le gradient de répartition des cations n'obéit plus aux lois de Ramberg et de Barth, car des phénomènes différents de ceux admis par ces auteurs, peuvent alors intervenir à l'échelle atomique.

(a) *Éléments perturbateurs d'ordre interne.*—Au niveau où se produisent les transformations



allotropiques ou des inversions de champs interfaciaux, la migration des éléments est fonction de la distance, à la zone de perturbation (migmatisation—granitisation).

La répartition véritable des cations pourra ainsi être l'inverse de celle prévue en fonction du champ de la pesanteur, d'après les calculs de Barth [3] ou par la cristallisation-différenciation. Prenons, par exemple, le cas du Massif Central en calculant par la méthode, si précieuse de Ramberg [14], de la cellule oxygène standard, les analyses publiées par M. Roques [18].

On constate, d'après le diagramme, ci-joint (Fig. 4), que le quantité de cations varie en sens inverse de ce qui est prévu d'après le champ de gravité. La zone de migmatisation qui représente la partie profonde de la zone de métamorphisme, a le moins grand nombre de cations de toute la série. Ainsi, la zone de migmatisation paraît correspondre à un foyer d'hyperdiffusion d'où émigrent les cations vers les parties supérieures. Ceci confirme entièrement les conceptions des partisans du transformisme crustal, avec Backlund [2], Reynolds [15], Kranck [12], Rittmann [17], Wegmann [19].

Trois facteurs principaux fixent la répartition des cations en cours de migration, la grosseur relative des ions, leur tension électropositive et leur affinité avec l'oxygène. Si l'on veut établir les lois de ce phénomène, il faut utiliser non la thermodynamique classique des fluides, mais la mécanique statistique du type Boltzmann, en y introduisant des facteurs d'interaction atomique et moléculaire, comme cela a été fait pour les calculs d'énergie intercrystalline.

(b) *Perturbations d'ordre externe.*—Pour illustrer le rôle d'un apport d'origine externe dans la zone superficielle, nous prendrons un exemple bien défini [8], celui du laccolite du Djebel Arroudjaoud (Algérie). Cette intrusion de roche grenue (granite et monzonite, quartzique), forme un laccolite

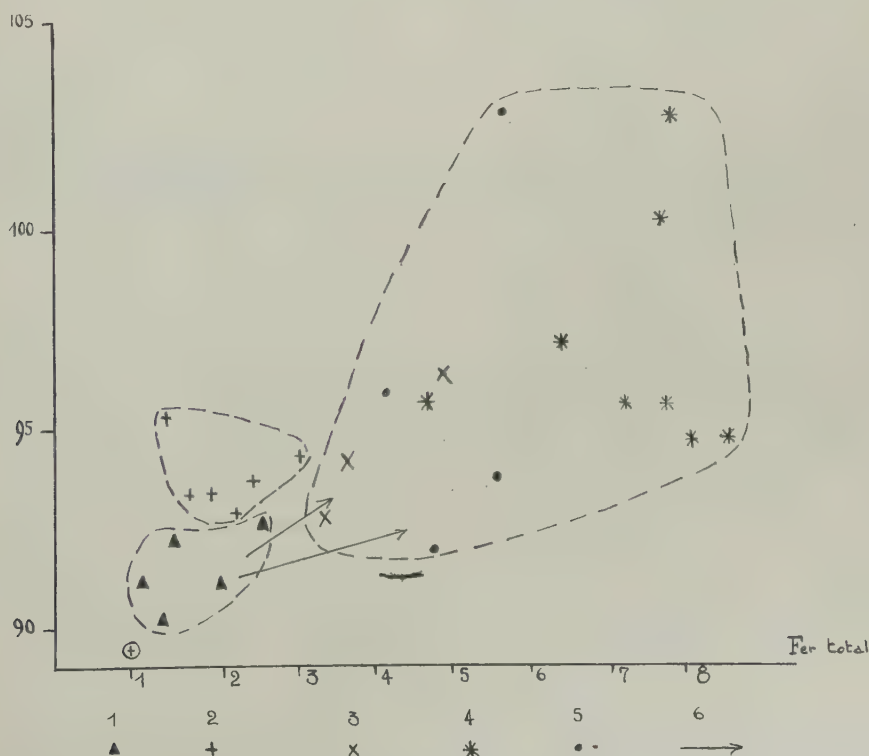


FIG. 4.—Variation du nombre de cations dans les formations métamorphiques du Massif Central.

1, migmatites ; 2, granites intrusifs ; 3, gneiss ; 4, roche métamorphique ortho (amphibolite, etc.) ; 5, schistes et micaschistes. En ordonnées : le nombre de cations pour 160 atomes d'oxygène (cellule standard de Barth). En abscisses : la quantité d'atomes de fer dans la cellule standard d'oxygène. Analyses de la thèse de M. Roques.

d'environ 250 m. d'épaisseur à l'intérieur des marnes miocènes. On connaît la partie supérieure et la partie inférieure du laccolite, ainsi que sa cheminée.

Etant données les conditions géologiques locales, la masse éruptive a dû s'injecter dans les marnes parallèlement à leur stratification. Il ne peut être question ici d'un front de granitisation. L'intrusion a dû se produire à moins de 800 m. de profondeur. La modification de marnes miocènes s'est étendue à environ 50 cm. au toit et à 3 m. à la base. Sur cette épaisseur relativement minime, des apports de silice, d'alumine, de fer et de magnésie se sont produits, en formant plusieurs fronts (Fig. 5).

À la partie supérieure, nous n'avons distingué qu'un front de migration, on peut en séparer 3 à la partie inférieure. Les deux premiers fronts (Si, Fe et Al, Mg) paraissent s'être produits par diffusion, à l'état solide, en donnant des cornéennes, tandis que le troisième (Ca) correspondrait à une phase pneumatolitique ultime, ayant donné des sphérolites de prehnite. La différence d'épaisseur du métamorphisme au toit et au mur, ainsi que la durée probable du refroidissement du laccolite, permettent de donner un ordre de grandeur de la vitesse de diffusion de ces éléments de 2 m. par  $10^6$  années, à la partie inférieure.

#### IV. MÉTASOMATOSE PROFONDE ET FORMATION DES MAGMAS

Les échanges diffusifs que nous venons d'observer entre une intrusion éruptive superficielle et des marnes, doivent augmenter en profondeur. Ils atteindront un maximum aux niveaux où l'intrusion traverse une zone de désordre oligophasé. Le milieu simique s'enrichit alors plus rapidement en silice et en éléments alcalins par une diffusion sélective analogue à celle du métamorphisme général, tandis que les parois sialiques limitant l'intrusion, reçoivent des éléments cafémiques.

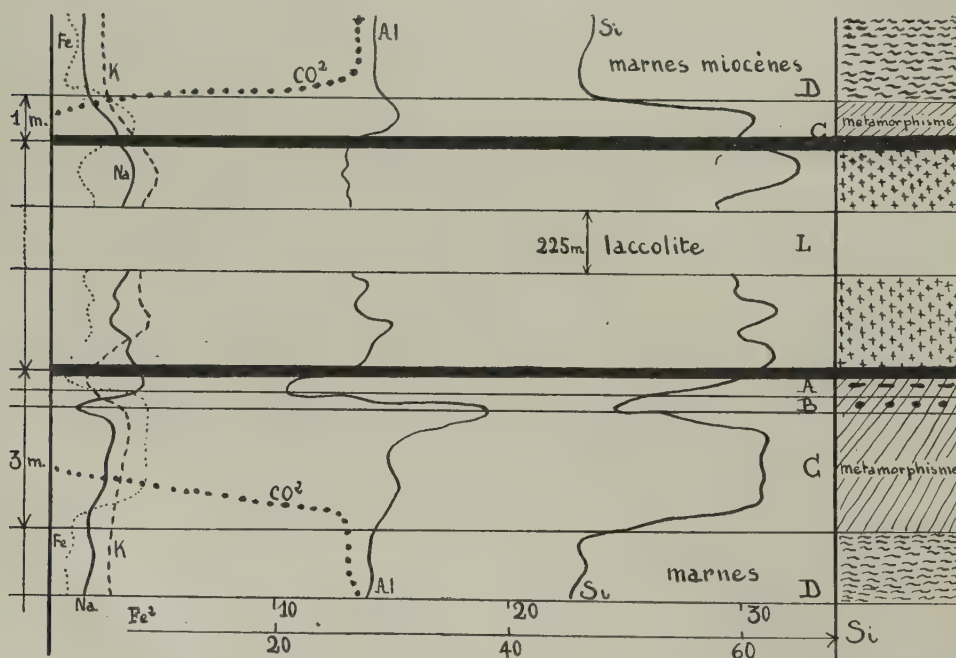


FIG. 5.—Phénomène de métamorphisme aux parties inférieure et supérieure du Laccolite du Djebel Arroudjaoud (feuille de Cherchel), Algérie.

En ordonnées : les distances au-dessus et au-dessous du contact entre les marnes miocènes et les roches grenues (épaisseur du laccolite L : 225 m.). En abscisses : pourcentage de différents éléments chimiques (Fe, Na, K,  $\text{CO}_2$ , Al, Si) (échelle spéciale pour  $\text{SiO}_2$ ). A, diopside feldspathique ; B, cornéenne à sphérolites de prehnite ; C, cornéenne sans prehnite ; D, marnes du Miocène moyen (marnes carténiennes).



Ce phénomène d'échange (contamination, transfusion, hybridation) entre un sima intrusif et les roches encaissantes, a été invoqué par de nombreux volcanologues: Anderson [1], Daly [4], Harker [9] Holmes [10], Kennedy [11], Richey [16], Rittmann [17], Wegmann [19], etc. Nous avons montré la nécessité de ce phénomène dans le cas du massif volcanique du Mont-Dore. La conception de l'état oligophasé apporte une explication physique aux faits géologiques invoqués par les auteurs précédents. Si l'on admet la "contamination" des magmas, il devient logique de chercher les rapports et les différences existant entre ce phénomène et le métamorphisme.

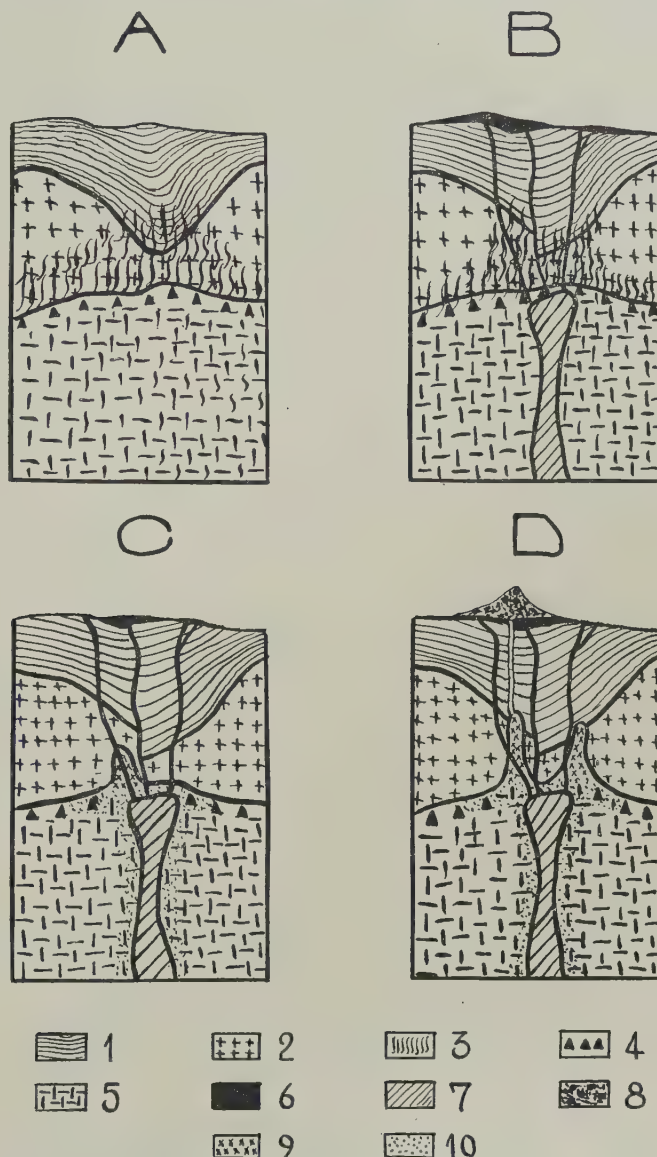


FIG. 6.—*Evolution d'un volcan complexe sialo-simique.*

Figures commun à toutes les figures : 1, sédiment ; 2, socle primaire ; 3, diffusion du métamorphisme général ; 4, niveau de migmatisation ; 5, migma granitique ; 6, filons et coulées de basalte ; 7, intrusion basaltique profonde ; 8, volcan rhyolitique ; 9, granite intrusif ; 10, zone de diffusion péri-basaltique.

FIGS. A et B : intrusion simique et formation de filons et volcans basaltiques. FIGS. C et D : montée des plutons granitiques et volcans rhyolitiques en surface. Les autres magmas sont déjà des magmas hybrides

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Or les éruptions volcaniques représentent des prélèvements successifs dans le milieu profond en voie d'évolution. L'étude des séquences volcaniques permettrait ainsi d'établir une chronologie exacte des phénomènes de métasomatose profonde. Les volcans de surface peuvent en effet être datés avec une précision relative plus grande que les phénomènes métamorphiques profonds. Mais à la diffusion atomique du métamorphisme s'ajoute le déplacement en masse, des magmas éruptifs. Nous allons montrer que le 2<sup>ème</sup> phénomène est l'aboutissement du premier.

En effet, les magmas profonds, riches en cations arrivent dans les régions supracrustales avec des températures plus élevées que le milieu ambiant. La zone dynamosensible (D.S.) en état de désordre oligophasé déjà réactivée, vit son niveau énergétique, augmenter brusquement par le déséquilibre chimique ainsi produit et par l'apport de température de la masse intrusive [20].

Cette réactivation et l'accroissement de la température ne se traduisent par seulement par des réactions chimiques et des phénomènes de diffusion. La viscosité du milieu sialique oligophasé

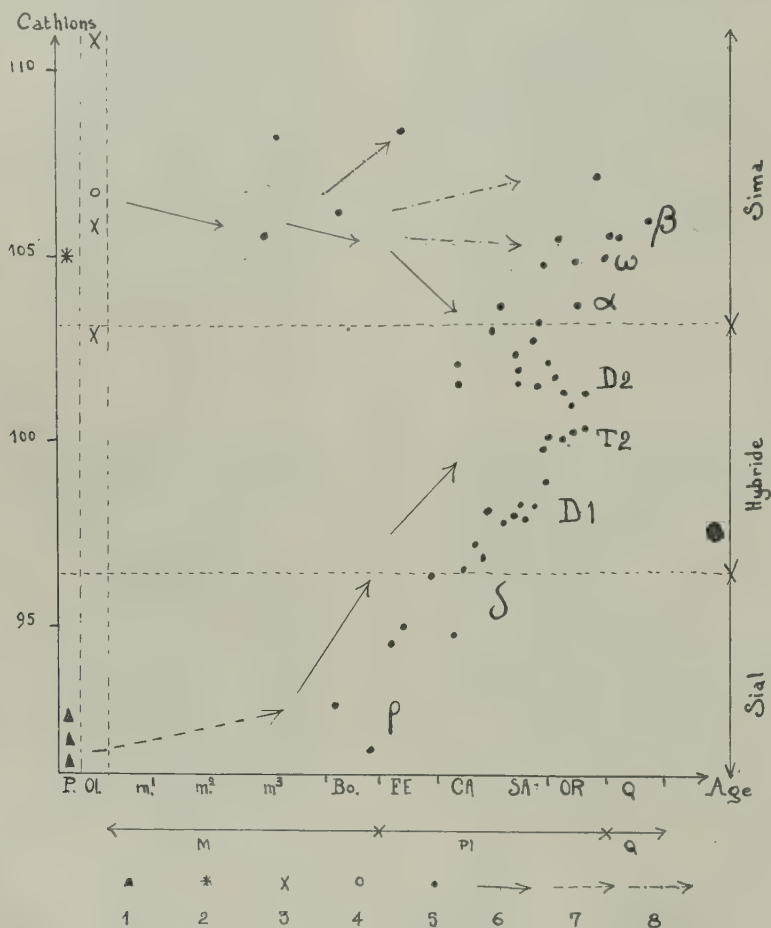


FIG. 7.—Evolution des magmas du Massif du Mont Dore.

En ordonnées : le nombre de cations pour 160 atomes d'oxygène (cellule standard de Barth). En abscisses : les différentes phases géologiques éruptives, d'âge miocène et quaternaire (pour plus de détail voir L. GLANGEAUD, *Bull. Soc. géol. France.*, 5<sup>e</sup> sér., 13, pp. 419-440, 1943. 1: migmatite primaire du socle, calculée d'après les analyses de Roques [18]; 2, idem : roche intrusive simique d'âge primaire ; 3, roches simiques d'âge oligocène et miocène inférieur (Puy de St. Sandoux); 4, basanite d'âge aquitainien de Gergovie ; 5, roches éruptives du Massif du Mont Dore : g, rhyolite ; S, sancyite ; D1, D2, Doréite ; T2, trachyte et phonolite ; α, andésite ; ω, ordanchites ; β, basaltes et basanites ; 6, évolution par hybridation ; 7 et 8, montée directe des magmas sialiques et simiques sans modification.



diminue aussi rapidement. Elle peut atteindre localement le seuil de fluidification au delà duquel la partie la moins visqueuse monte à travers la plus visqueuse.

En effet, ainsi que l'ont montré les études modernes de Darrois [5], Eyring [6], de l'Ecole de Princeton, etc., la viscosité et la plasticité du milieu sont liées aux coefficients d'activation.

La plastification du milieu se produira d'abord dans une zone limitée autour des intrusions simiques et formera comme une sorte de gaine autour de celles-ci (Fig. 6). Quand ces plutons granitiques d'origine palingénétique, arrivent en surface, ils donnent les dômes rhyolitiques bien connus dans un certain nombre de volcans complexes où ils sont intercalés entre des venues basaltiques provenant d'une profondeur différente (Fig. 6).

Mais, en même temps, au voisinage des intrusions basaltiques, se produit une intense métasomatose, au niveau de la zone oligophasée entre le migma granitique et l'intrusion basaltique. Ce phénomène tend à redonner des roches hybrides, par diffusion réciproque des éléments. Les deux exemples que nous avons déjà publiés sur le Massif volcanique de Mont Dore (Fig. 7), dans le massif Central de la France et dans la bordure littorale de l'Atlas algérien (Fig. 8) montrent la similitude de l'évolution des magmas dans ces deux régions si différentes.

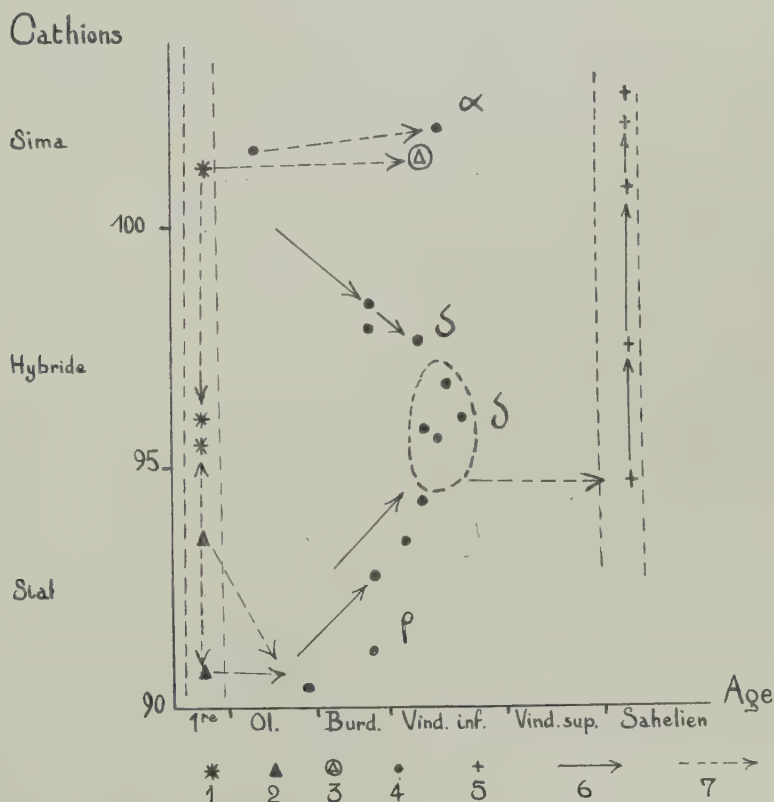


FIG. 8.—Evolution des magmas dans la région littorale de la province d'Alger, pendant le Miocène.

En ordonnées : cations pour 160 atomes d'oxygène. En abscisses : les temps géologiques. Pour plus de détail voir notice L. GLANGEAUD, carte géologique Alger au 500,000<sup>e</sup> (Bull. Serv. Carte géol. Algérie, 1939 et travaux antérieurs). 1, roche simique et hybride d'âge primaire ; 2, roche sialique d'âge primaire ; 3, roche intrusive simique d'âge miocène (dolérite à olivine) ; 4, roche d'épanchement d'âge miocène : ρ=rhyolite ; δ=dacite et dacitoïde ; α=andésite labradorite ; 5, roche intrusive d'âge miocène supérieur (granite et monzonite quartzifère, etc.) ; 6, phénomène d'hybridation ; 7, montée directe du magma sans modification.

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Il est à noter que, dans les deux cas, nous connaissons le socle où ont dû se produire les phénomènes de palingénèse. D'intéressantes analogies existant entre les formations du socle (triangle) et les produits volcaniques tertiaires provenant, soit de la palingénèse du socle (rhyolite, granodiorite), soit de la contamination des magmas basaltiques (sancyite, doréite, trachyte, phonolite, etc.).

Si l'on en juge par la vitesse d'évolution des magmas du Mont Dore et de l'Algérie, la durée nécessaire pour une telle contamination est de l'ordre de grandeur d'un tiers à un quart du Pliocène ou d'un étage du Miocène. Elle sera de l'ordre de 2 à 5. 10<sup>6</sup> années, d'après la chronologie d'Holmes [10]; Ainsi le phénomène de métasomatose profonde serait géologiquement rapide. En effet, la durée du Cambrien serait dans la chronologie de 20 à 30 fois plus longue que l'évolution du Mont Dore. Seule une analyse très fine du phénomène profond comme l'ont fait Wegmann [19], les Scandinaves et l'Ecole d'Edimbourg, permet donc d'obtenir des résultats réels dans le métamorphisme. Une chronologie trop grossière ou des courbes purement chimiques risquent de superposer plusieurs processus successifs et différents. Un tel " mélange " artificiel n'a plus aucune signification géologique.

#### V. VITESSES RELATIVES DES DIFFUSIONS IONIQUES

Ainsi les vitesses différentes de diffusion de chaque élément représentent le phénomène dominant, pour l'évolution des magmas volcaniques comme pour le métamorphisme. Peut-on pousser plus loin les analogies et trouver, dans les séquences volcaniques, des rythmes rappelant les fronts de migration chimique de Backlund, Doris Reynolds, Wegmann. Une telle étude ne peut encore être actuellement qu'ébauchée. Néanmoins, dans le Mont-Dore, il semble apparaître des variations chimiques de *deuxième ordre dans les phases d'hybridation* (CA) (SA) (OR). Ces " pulsations " café-miques et alcalines pourraient être, *dans le volcanisme profond, l'analogue des fronts de migration chimique du métamorphisme général.*

En effet, comme nous l'avons vu, la pétrogénèse profonde n'obéit généralement pas aux lois simples de la thermodynamique des solutions.

Wegmann [19] a bien montré en 1933, 1934, que les cations de petites dimensions sont plus mobiles que les gros anions. Ces derniers constituent donc, par rapport aux premiers, un réseau presque stable. Il est, en cela, d'accord avec Ramberg et Barth; mais la vitesse de migration des cations dans ce réseau, dépendra de plusieurs facteurs.

(1) Les cations les plus petits peuvent évidemment traverser plus facilement les mailles, ainsi que l'ont supposé plusieurs auteurs à la suite de Goldschmidt [7] et notamment récemment Lapadula-Hargues [13] mais la *grosseur des cations* n'est pas un fait concret et rigoureux. C'est une *image statistique*, commode dont on ne doit pas abuser. Il faut tenir compte des phénomènes ioniques, qui modifient considérablement les sphères d'action des atomes, de la déformation de celle-ci et de la polarisation concomittente.

(2) *L'affinité avec l'oxygène* à la température métallurgique retient les cations les plus oxydables (Ca, Mg, Al, Si).

(3) *La tension de polarisation.*—A température moins élevée les ions les plus électropositifs sont retenus plus facilement par les chaînes (SiO<sub>4</sub>)—Les plus électropositifs sont rangés dans l'ordre de positivité décroissante: K (2, 9), Na (2, 7), Ca (2, 7), Mg (1, 5), etc.

(4) *La densité* dans le champ de la gravité, est fonction de l'état ionique, car les dimensions de l'atome varie dans cet état.

(5) *Le nombre de transport* joue aussi son rôle:—

Une partie des métaux peuvent avoir ainsi au moins deux comportements suivant la profondeur. Par exemple, pour Ca et Mg: à haute température, c'est leur affinité, avec l'oxygène qui les retient (scorie d'oxydation). A température plus basse, c'est la tension de polarisation qui entre en jeu et ils émigrent plus facilement. Il en est de même pour Si. Ainsi les migrations sont différentes dans le métamorphisme à faible profondeur du Djebel Arroudjaoud, où le Si est très mobile (Fig. 5) et dans le métamorphisme général (Fig. 4) où le Si reste fixé dans les chaînes (SiO<sub>4</sub>).



D'accord avec Wegmann [19], on peut considérer du point de vue de la profondeur, deux zones successives de métasomatose profonde. Dans la zone supérieure des Fig. 3 et 6, une partie seulement des cristaux est transformée, la trame d'oxygène est relativement stable et les cations diffusent notamment en fonction de leurs dimensions par rapport au réseau et de leur tension électropositive. Les cristaux sont ainsi entourés d'une gaine d'ions émigrants formant le film intergranulaire de Wegmann. C'est la zone que l'on peut qualifier de zone de métamorphisme général qui exige un temps relativement assez long pour se développer intégralement.

Mais le stade du film intergranulaire est dépassé en profondeur où toute l'épaisseur des réseaux cristallins s'est perturbée. Au commencement de l'évolution, les éléments qui pourront se dégager le plus rapidement sont le Fe et Mn, étant donné leur position dans la liste des affinités électropositives Fe = 0,43, Mn = 1, v, 08. Après le Fe, ce sont les ions basiques Mg (7, 55) et Ca (2, 7) qui tendront à émigrer.

Ils donneront ce que Reynolds a appelé des *fronts basiques*. Nous en avons constaté l'existence dans les quartzites de la zone des schistes lustrés dans la région de Bastia (Corse). A une profondeur plus grande, l'état de désordre a tendance à gagner toute la masse par un phénomène d'autocatalyse. Les gros ions alcalins, Na, K, électropositifs avec (2, 7) et (2, 9) e.v. deviennent eux-mêmes mobiles. C'est le *front alcalin* de Doris Reynolds.

Ainsi, au-dessus, de la zone de granitisation, les fronts de migration donnent des roches enrichies en cations. La zone de migmatisation est, au contraire, appauvrie en cations, comme le montrent les diagrammes du Massif Central (Fig. 4). La zone de granitisation a donc, d'abord perdu tous les cations en excédent par rapport à la composition sialique normale. Le milieu s'est homogénéisé. C'est le migma granitique ayant acquis la composition chimique d'un granite moyen. Il est, à ce moment, à l'état oligophasé. Dans cet état, les chaînons SiO<sub>2</sub>—libres comme dans un verre, sont entourés surtout d'ions Na, K, monovalents ayant la plus forte tension électropositive avec des résidus plus ou moins abondant de cations migrants: Ca, Mg, Fe.

Ce n'est que secondairement, sous des pressions plus faibles, que ce migma cristallisera comme un verre ou montera vers la surface, sous forme de magma du type fondu.

#### CONCLUSIONS

Un mécanisme de diffusion à l'échelle atomique basé sur des données expérimentales de la physique atomique moderne réunit dans une théorie homogène, les faits géologiques du volcanisme, de l'évolution des magmas, du métamorphisme et de la granitisation. L'avenir dira ce que l'on peut conserver de cette hypothèse de travail.

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### DISCUSSION

L. NELTNER demande à M. Glangeaud sur quelle bases ont été établis les diagrammes présentés relatifs aux variations de température et de vitesses de diffusion.

L. GLANGEAUD: Les diagrammes présentés font intervenir deux éléments : (a) Des éléments quantitatifs expérimentaux sur les variations des propriétés des solides au voisinage des zones de transformation allotropique. (b) Des données géologiques et pétrogénétiques. L'auteur a notamment utilisé les beaux travaux de l'Ecole Scandinave et de l'Ecole Ecossaise sur les migmatites et le métamorphisme.



# DIFFERENTIAL MOBILITY OF COMPONENTS AND METASOMATIC ZONING IN METAMORPHISM

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## ABSTRACT

The metamorphism of silicate rocks proceeds only with the aid of ascending solutions, which may either rise through a system of fissures or percolate through rock masses. In the first case metasomatic diffusion-zoning develops along the fissures. In the second case metasomatic filtration-zoning develops, depending on the alteration of solutions that penetrate through the rock. Besides that, certain rocks may react with each other, with the participation of the components of ascending solutions and resultant formation of contact metasomatic diffusion-zones (skarn, lazurite and other contact zones). In all these cases rock replacement proceeds discontinuously, with the simultaneous growth of several sharply defined zones, composed of reaction minerals. From zone to zone the number of minerals gradually decreases down to the most altered monomineralic zone. This is due to the differential mobility of components, thought to result mainly from the differences in their respective solubilities.

Attention is directed to the evidence of accumulation of the less soluble components in definite zones and to the phenomenon of metasomatic contraction of rocks. Filtration-zoning differs from diffusion-zoning in the possibility of a direct deposition of certain minerals from solution and in the absence of equilibrium in zone boundaries.

A STUDY of metamorphic rock complexes shows that in metamorphism, at least of silicate rocks, ascending solutions always take part. This conclusion is supported by the fact that metamorphism is always displayed non-uniformly, being more intense along certain zones and weaker, or even completely lacking, elsewhere ; the more intense metamorphism (recrystallization) is always accompanied by a partial change in the chemical composition of the rocks, i.e. the phenomena are metasomatic. Such a lack of uniformity cannot be accounted for by a non-uniform distribution of temperature, of deformation or of groundwater content ; it thus points to the necessary participation of ascending solutions which saturate the pores of rocks of definite zones, giving rise both to recrystallization of the rocks concerned and to a change in their chemical composition. In rocks in which the recrystallization process has not been completed, partly decomposed minerals often retain abundant microscopic inclusions of the solution that corroded them ; such, for instance, are the turbid feldspars, erroneously described as " kaolinized."

The interaction between ascending solutions and rocks may be effected in various ways, two extreme possibilities being distinguishable. (1) The solution ascends an open fissure and permeates the pores of the wall-rocks. The interaction between the flowing solution in the fissure and the wall-rocks is implemented by diffusion through the immobile pore-solutions of the walls of the fissure. Such a fissure—wall-rock metamorphism is particularly characteristic of low temperature conditions, when fissures are readily formed and rocks are poorly permeable to the flow of solutions. (2) The solutions uniformly percolate through the rocks so that each grain of rock directly interacts with the flowing solution, without any essential participation of diffusion processes. Such a mechanism is characteristic for high and medium temperature conditions, when the rocks are more permeable to the solutions and the formation of fissures is impeded.

It is probable that in reality the most common mechanism of metasomatism is a combination of the two limiting cases outlined above. On the one hand, in zones of percolation, diffusion probably always plays a certain part, at least in replacing the inner parts of grains ; moreover, the percolation may be non-uniform as a result of the co-existence of less permeable regions with stagnant pore solutions. But a particular complication is introduced by the " filtration effect," whereby the dissolved substance is not only transported by the percolating solvent, but also in part diffuses through it. The

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more rapid the filtration and the lower the concentration of the solution, the less is the part played by diffusion. On the other hand, the fissures in the earth's crust are rarely open and the ascent of solutions through them is most frequently not a simple flow, but rather of the nature of percolation, although here the percolation proceeds at a more rapid rate than through massive rocks. Nevertheless, the distinction between the two extreme types of interaction of solutions with rocks retains its significance.

A theoretical interpretation of metamorphism is greatly facilitated by the natural assumption that the pore solutions are in chemical equilibrium with the rock directly enclosing them. The existence of chemical equilibrium is proved in particular by the phenomenon of collective recrystallization which is highly typical of metamorphic and metasomatic rocks. Owing to the existence of surface energy, small grains are somewhat more readily soluble than large grains of the same mineral. Therefore simultaneously with the dissolution of small grains there may take place a growth of larger ones. The solution is in equilibrium with crystals of a certain medium size, i.e. the equilibrium of the rock and the solution is very precise. The largest crystals are formed with a minimum concentration of the solution, when the existence of small and medium grains is impossible; therefore the number of crystalline grains is small. In particular, the growth of especially large crystals frequently takes place under conditions of dissolution and removal of the substances of the given crystals by moving solutions, which at first sight seems to be paradoxical. With a decrease of the concentration of the solution and with the dissolution of small crystals and removal of their substance, the growth of single large crystals continues, the growth of some faces being sometimes accompanied by corrosion of others; with further decrease in the concentration of the solution, dissolution of the largest crystals begins to take place. Thus the formation of corrosion-vugs is, as a rule, accompanied by the formation on their walls of crusts of large crystals, as observed in miarolitic vugs, rock-crystal cavities, and veins of Alpine type. It is generally assumed that the formation of a vug takes place first, followed by the growth of large crystals on its walls. However, a number of data constitute evidence indicative of the simultaneous occurrence of both dissolution and growth. Such, for example, is the common "coating" on rock crystal faces (sometimes on faces that were subsequently overgrown, so that they became included within the crystal) of flakes of sericite, chlorite and other minerals released in consequence of a general dissolution of the enclosing rock; such are the free crystals which, although separated from the walls by dissolution, continued to grow on the floor of a cavity (N. Permakov, 1946). A similar growth of large crystals under conditions of dissolution is observed in metasomatic rocks. Thus the well known spotted "smallpox" magnetite ores of Mt. Blagodat in the Urals, were formed metasomatically by a replacement of syenite-porphyrates. The replacement of fine-grained orthoclase syenite-porphyry by magnetite is accompanied there by the growth of single large orthoclase crystals which remain as phenocrysts in the magnetite mass. During silicification of various rocks, large crystals of the replaced minerals are usually formed in the transitional zone, e.g. feldspars or micas in pegmatites and greisens, calcite in limestones, etc.

Thus, an equilibrium of solutions with respect to the enclosing rocks is typical of the metasomatic phenomena associated with metamorphism. Undersaturated solutions, producing dissolution without recrystallization, and oversaturated solutions, out of which colloids may be precipitated, mainly appear in fissures not far from the earth's surface and during weathering. In metamorphism they are not characteristic.

If a solution comes into contact with a rock and its concentration differs from that of equilibrium, a reaction between the rock and the solution proceeds with the formation of "reaction minerals" in the rock, to the composition of which the components of the rock alone or those of both the original rock and the solution may contribute. The composition of both rock and solution thus varies, and in this way equilibrium is attained. In some cases the formation of non-reaction "precipitated" minerals is possible; these are entirely precipitated from the solution, without deriving any components from other minerals. The cause of such a precipitation of a mineral may be the decrease of its solubility, produced by fall of temperature or pressure in the solution, or by a change in the composition of the solution as the result of the solution of other minerals of the rock. The cause of the precipitation may



also lie in the rise of the concentration of the solution, produced by a narrowing of the pores in the passage-ways of the percolating solutions, i.e. by the filtration effect (Mackay, 1946 ; Korzhinsky, 1947).

During metasomatic phenomena the various oxides and elements which compose a rock display an independent behaviour. Solutions acting upon the rocks fail to produce any marked displacement of certain components, while at the same time noticeably changing the composition of the rocks with respect to other components. In this way the "differential mobility" of elements is manifested, which is of outstanding importance in metasomatic as well as in magmatic processes. In the metasomatic alteration of a rock a "metasomatic zoning" is produced as a result of the differential mobilities of its components. This is displayed in the simultaneous existence of several zones representing different degrees of alteration of the original rock. One should distinguish a metasomatic "diffusion-zoning" characteristic of fissure—wall-rock metamorphism and of contact formations due to reaction, and metasomatic "infiltration-zoning" characteristic of the zones of percolating solutions. In the present paper the infiltration-zoning will be mainly discussed.

The infiltration-zoning is produced because the solution which penetrates into the rock and changes its composition also undergoes a change and therefore, upon further percolation, induces an alteration of the rock which is different from the initial one. As a result of this, zones with different mineralogical compositions should be formed along the course followed by the solution. Let us assume that we have a thick uniform mass of a polymineralic rock. In the uppermost zone there will percolate a solution of which the composition has been altered as result of an interaction with the rock at lower levels to such an extent that it will now be capable of producing only a simple metamorphism of the rock, bringing about a change in the water content but not in the other components. On the contrary, in the lowermost zone the rock will be changed by reaction with the fresh, unaltered, solutions which will flow through it to such a degree that complete equilibrium will be attained. Between these extreme zones, others showing transitional degrees of alteration will be situated.

In order to establish the peculiarities of infiltration-zoning we shall confine ourselves, for the sake of simplicity, to the case of constancy of temperature and external pressure for all the zones, uniform porosity (i.e. constancy of the filtration effect coefficient) and constancy of composition for each of the minerals.

At each point, as we have seen, the solution must be in equilibrium with the enclosing rock. This equilibrium is not disturbed by a change in the quantitative proportions of the minerals, but only by a qualitative change of the mineral composition. Therefore the reaction of the percolating solution with the rock takes place only on the boundary between two zones of different mineral composition, whereas within each zone no interaction occurs. With a uniform initial material each zone has a constant mineral composition.

The quantity  $dm$  of the dissolved component, which is transported by the percolating solution through any section transverse to its flow, is equal to the product of the volume  $dv$  of this solution by the concentration  $c_a$  within it of a given component  $a$ , and by the filtration effect coefficient  $\varphi_a$  (coefficient of entrainment by the solvent) for the given component in a given medium. Thus we have,

$$dm = \varphi_a \cdot c_a \cdot dv.$$

With a free flow of the solution, when the dissolved substance is completely entrained by the flow of the solution, the coefficient  $\varphi$  is equal to unity. In the case where the medium allows the solvent to percolate through but completely abstracts the given component dissolved in the solution, this coefficient is equal to zero.

The filtration effect is caused by the difference of the average rate of movement of the particles of the solvent and the solute in a porous medium and not by adsorption phenomena. The magnitude of the filtration effect during filtration through rocks, particularly at high temperatures, is not known, but doubtless the coefficient may differ considerably from unity. But in this particular case this coefficient has been introduced only for completeness, since metasomatic zoning may also develop independently of the filtration effect.

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Now the contact between two metasomatic zones I and II, with a solution percolating in the direction from zone II towards zone I will be considered. The content of the  $a$  component per unit volume in zone I will be designated as  $a'$ , and that in zone II,  $a''$ . The concentration of this component in the solution within zone I will be designated as  $c'_a$ , and that for zone II as  $c''_a$ . The elementary volume of the solution  $dv$ , which will percolate across a unit surface of contact, will bring the  $a$  component from zone II towards the point of reaction in the amount:  $\varphi a \cdot c''_a \cdot dv$ , and carry it away towards zone I in the amount  $\varphi a \cdot c'_a \cdot dv$ . Let the contact of the zones advance by the distance  $dx$ , as a result of the passage of this elementary volume of solution. If the replacement takes place without change of volume, as is generally assumed, we should have the equation:

$$\varphi a (c'_a - c''_a) dv = (a' - a'') dx.$$

Hence we obtain the ratio of the rate of advancement of the boundary of the two zones to the rate of percolation:

$$\frac{dx}{dv} = \varphi a \frac{(c'_a - c''_a)}{(a' - a'')}$$

An analogous expression may be obtained for each of the components. Since in all expressions of this kind we are concerned with the rate of displacement of the same boundary, we obtain:

$$\frac{dx}{dv} = \varphi a \frac{c'_a - c''_a}{a' - a''} = \varphi b \frac{c'_b - c''_b}{b' - b''} = \varphi d \frac{c'_d - c''_d}{d' - d''} = \dots$$

If upon the replacement of rock I by rock II the volume increased  $m$  times, we should obtain:

$$\frac{dx}{dv} = \varphi a \frac{(c'_a - c''_a)}{(a' - ma'')} = \varphi b \frac{(c'_b - c''_b)}{(b' - mb'')} = \varphi d \frac{(c'_d - c''_d)}{(d' - md'')} = \dots$$

In this way  $n-1$  equations are obtained, relating the values of the contents and concentrations of  $n$  components in two adjacent zones. The very fact of the existence of these equations enables us to draw some conclusions concerning the number of minerals in metasomatic zones.

With constant temperature and external pressure the state of an equilibrium mineral system of  $n$  components is determined by  $n$  independent factors, which are determined by external conditions. Each component introduces one independent factor of equilibrium. For less readily soluble ("inert") components the independent factor will be determined by their content in the rock, depending on the original composition. For the other, i.e. "fully mobile" components, the independent factor is determined by their activity in the external medium or by their concentration in the incoming solution. If the minerals being formed do not permit of any variations of composition, the number of co-existing minerals in the rock is equal to the number of components with an independently defined content (i.e. to the number of "inert" components). The number of "mobile" components, with an independently defined activity, is equal to the difference between the number of components and the number of minerals.

Let us compare two adjacent zones of the filtration column. In the first and uppermost zone the original composition of the rock, with the exception of the water content, has not yet changed. The contents of all components (if water be excluded from the components) are independently defined by the original composition of the rock, and therefore  $p$ , the number of the minerals formed in metamorphism, should be equal to the number of components ( $p=n$ ). In the adjacent second zone, formed at the expense of the first zone by the action of the solutions, the state of the rock will be determined both by the composition of the original rock and by the concentration of the acting solutions. But we have seen that there are  $n-1$  equations relating the values of the contents and concentrations of components in two adjacent zones. Therefore of  $n$  independent parameters determining the state of the rock in the second zone, only one may be conditioned by the concentration of the solution (concentration of the most mobile component), while the remaining ones, by means of the  $n-1$  equations, are defined by the content of components in the first zone. Owing to the existence of one independently



defined concentration, the number of minerals in the second zone will decrease by a unity, i.e. will be equal to  $n-1$ .

In the third zone the parameters of state, by means of the same  $n-1$  equations, are related not only to the content of the components in the second zone, but also to one independent concentration of the mobile component of this second zone. Therefore in the third zone two components may thus have an independent concentration, i.e. may be mobile, and the number of minerals will decrease by one more. Thus with every passage to a lower zone the number of inert components and the number of minerals decreases by one, the number of mobile components increasing accordingly. In the particular case when for a definite concentration of the mobile component the conversion of one mineral association into another is possible without any decrease in the number of minerals, an equal number of minerals and inert components may be found in the adjacent zones. In the lowest, most strongly altered zone, the number of reaction minerals may drop to one or even to zero in the case when all the components of the original rock have been removed and the rock has been completely replaced by the precipitated mineral.

A number of features of infiltration-zoning may be anticipated on the basis of the above equation for the rate of advance of the zone-boundary, considering that the rate of advance for each higher zone must be greater than that for a lower zone. The chief features of this zoning are as follows :

(1) As a result of the action of percolating solutions on a multi-component rock a number of sharply delimited metasomatic zones must be formed, and these will increase simultaneously, the lower ones advancing upon the upper ones.

(2) The replacement takes place only at the boundary of the zones. Within the zones a change of composition only of variable minerals is possible.

(3) In each zone one may distinguish "inert" components, the amounts of which are determined by their amounts in the original rock, and "mobile" components, whose amounts depend on the proportion of the inert ones and on the concentration of the solution but not on their initial amounts. The number of minerals is equal to that of the inert components. Therefore conclusions as to the inert or mobile behaviour of components during metasomatism must be confirmed by comparing the number of the components with that of the minerals.

(4) From the upper to the lower zone the number of inert components and the number of minerals gradually decrease, while the number of mobile components accordingly increases.

(5) The higher the solubility of a component and its ability to percolate with the solvent, the earlier its passage to the mobile state ; inertness is maintained even in the lower zones by the least soluble, i.e. the least mobile components.

(6) At the boundary of two zones, due to replacement reactions, the concentration of a percolating solution sharply changes. Because of the equilibrium between the rock and the solution the rocks of the two adjacent zones must possess a different activity of the components, that is, they will not be in chemical equilibrium. As a result of this, some zones may be lacking, which would be formed as transition zones between the existing ones in the case of a diffusion-interaction.

(7) The dissolution and removal of part of the components of a particular mineral should result, according to the law of mass action, in an increase of the activity of the remaining components of that mineral. If all the components of a mineral are dissolved and removed, then there may be formed a zone of enrichment in the least mobile component of that mineral on the site of this zone of complete removal. Thus, at places of greisenization and subsequent silicification of feldspathic rocks, greisens enriched in alumina are encountered. Sericitic, andalusitic and corundum rocks rich in alumina, occurring amidst acid silicified effusives are probably of a similar origin.

Up to this point we have considered only reaction-minerals, i.e. those containing components of the original rock. But in addition to these, the solution may deposit some of its components as independent "precipitated" minerals. This may take place as a result of a change of the composition of the solution with penetration into the rock, owing to a possible influence of the concentration of certain components on the solubility of others. In this case the precipitation of the mineral must be

confined to definite zones, the nature and amount of the mineral deposited depending not only on the composition of the solution but also on that of the rock. Such "selectivity" of replacement is confirmed by observations. Next, observations have shown that during all post-magmatic processes, up to those of highest temperature, only one mineral is precipitated at a time, which not infrequently brings about the formation of monomineralic rocks. The latter takes place when rocks are silicified and when certain metasomatic sulphide ores and high-temperature magnetite ores are formed. The writer has not encountered any cases in which more than one mineral has been precipitated at a time during metasomatism. However, the theoretical aspect of this problem is not clear and it seems possible that under certain conditions more than one mineral may be deposited at a time, but in such a case the proportions of these minerals must depend on the composition of the rock being replaced.

*Metasomatic diffusion-zoning* arises in those cases when the replacement has been caused by a diffusion-exchange of the components. Its distinct manifestation is seen in the fissure-wall-rock metasomatism, when the solution rising up the fissure soaks into the wall-rocks. The interaction of the flowing solution of the fissure with the wall-rock is achieved by way of a diffusion of the components through the stagnant pore solutions in both directions, there being formed several sharply delimited reaction zones, similar to those formed in infiltration-zoning. In the outermost zone the action of the solution brings about a simple metamorphism without any change of composition, with the exception of water. In each successive inward zone an increasingly large number of components pass into a mobile state, with a corresponding decrease of the number of minerals, up to the innermost zone, usually a monomineralic one, adjoining the monomineralic vein-filling. All of these zones develop simultaneously, every outer zone being replaced by the inner ones. Such vein-wall-rock zones may attain a thickness of several metres. The theory of such zoning has been discussed by the writer elsewhere.

A more complicated case is that of metasomatic reaction-formations at the contacts of rocks that are not in chemical equilibrium. Descriptions and theoretical analyses of such formations are given in several papers by the writer. Thus, in a high-temperature metamorphism at shallow depths between limestone and silicate rocks skarn-zones are formed. Reaction-zones between hyperbasites and acid rocks are widely known. Under the conditions obtaining at great depths the reaction between dolomites and aluminosilicate rocks leads to the formation of phlogopite and lazurite deposits. It is characteristic that even in intensely metamorphosed gneiss-complexes such an interaction is extremely non-uniformly displayed. While in some parts of the contact the zone of interaction attains a thickness of several metres (in some exceptional cases up to some 20 metres), in other parts of the same contact it drops to some millimetres or less. Such non-uniformity proves that the interaction between rocks might have occurred only at the places where ascending solutions, soaking the pores of the rocks, were active. Thus the diffusion proceeded through pore solutions and not through solid matter. The part taken by ascending solutions is confirmed also by the fact that an intensification of the interaction is always accompanied by a supply or removal of the more mobile components (e.g. a supply of iron and magnesium in skarn-zones). Moreover, it is known that the interaction of the rocks becomes sharply intensified along fissures, so that the fissures intersecting the contact of the interacting rocks are converted to metasomatic veins, e.g. veinlets of lazurite rocks in pegmatites amidst dolomites, phlogopite- and skarn-veins. All the examples of interaction mentioned refer to post-magmatic but very high-temperature phenomena; the high temperature is inferred from the formation of such metasomatic minerals as plagioclases (up to anorthite), garnets, forsterite, spinel, lazurite, hauynite, nepheline, sanidine, orthoclase, etc.

Thus the metasomatic interaction of rocks takes place in zones where ascending solutions are percolating, under such conditions that the more mobile components (particularly carbon dioxide and alkaline metals, sometimes also magnesium, iron and others) are fully mobile. It is through these ascending solutions, if they percolate in the contact zone of rocks capable of reacting, that a diffusional exchange of the less mobile components proceeds, amongst which, during the formation of skarns, calcium, silica, and alumina are numbered. Such a complex interaction of two rocks and a



solution may be named *bi-metasomatism*. The reacting rocks are separated by several sharply defined zones with a small number of minerals, up to monomineralic zones (monomineralic garnet, pyroxene, phlogopite, jadeite, nephrite, talc and other rocks). The slight mobility of alumina, as compared with that of silica, brings about a metasomatic desilication which is very characteristic of bi-metasomatism. Removal of silica in conjunction with a decrease of the volume of the aluminosilicate rock leads to a sharp increase in the alumina content of some varieties.

A diffusional interaction may also take place between liquid magma and wall-rock. Great importance was attached to such an interaction by A. E. Fersman, who gave a detailed description of the migration of elements in both directions at contacts exposed in the emerald mines of the Urals (1925). Explorations of Pre-Cambrian gneissic complexes in Siberia have shown that very frequently granites and pegmatites form direct contacts, even with dolomites, without the formation of reaction zones; and that it is only at certain places that such zones are developed, under the action of post-magmatic solutions subsequent to the crystallization of granites and pegmatites.

Diffusional migration of a component is possible only provided that there exists an activity or concentration gradient in the solution. From the standpoint of the phase rule, the concentration (activity) of the mobile diffusing component has a degree of freedom; therefore the passage of each component into the mobile state is accompanied by a corresponding unit decrease in the number of minerals. The decrease in the number of minerals is a necessary sign both of the diffusion and of the infiltration migration of a substance. In this lies the resemblance of the infiltration-zoning to the diffusion-zoning. However, a point of distinction is presented by the fact that, as a rule, the diffusional metasomatic zones consist only of reaction minerals. A precipitation accompanied by the solution of the more readily soluble minerals takes place only in fissures and in those rocks in which the replacement occurs with decrease in volume (i.e. with a fall of pressure), only one of the minerals being precipitated at a time, just as in the case of infiltration. Sharp boundaries between the zones are typical of any metasomatic zoning, since they are not disturbed by the influence of non-uniform fracturing and porosity.

Although the writer has not been specially engaged in the study of granitization, it seems appropriate at this point to touch on this problem which is at present a subject of active discussion. Many authors (among Russian geologists, especially N. G. Sudovikov) at present favour a metasomatic origin for granites at the expense of a granitization of other rocks. The writer thinks the polyminerale composition of granites and the stability of their quantitative mineralogical composition are in conflict with the hypothesis of their metasomatic origin and cannot be explained without the aid of melting, i.e. of a magmatic stage. A diffusion of components through pore solutions or through solid rocks cannot produce any equalization of the proportions of the minerals. The concept of an exceptional rôle of diffusion through solid rocks during metamorphism is in conflict with geological observations of bi-metasomatic formations, as shown above, and in general with the distribution of metamorphism and diffusional zoning.

There is more reason for relating metamorphism and granitization to the action of the percolating solutions, as envisaged by P. Termier (1910). Juvenile ascending solutions, essentially aqueous, percolating through the sialic shell of the Earth, may cause its selective melting, with formation of a eutectic granitic magma. A considerable part of the juvenile volatile components is retained by the forming magma and it separates out only on crystallization of the latter, to which fact the particular intensity of post-magmatic metamorphism is due. Another part diffuses through the magma and then percolates through the rocks of the roof, causing their metamorphism and granitization. Here a metasomatic infiltration-zoning should be produced, the nature of which has been considered above. Higher up, the solutions cause a "normal metamorphism," during which only water and carbon dioxide behave in a mobile manner. Lower down, there follows a zone in which the activities of potassium and sodium have been brought to a level established in the underlying granitic magma, with a corresponding decrease of the maximum number of co-existing minerals. Therefore, with rise of temperature the metamorphism of this zone assumes the nature of granitization, particularly near

contacts with granites where selective melting begins. The lowest zone is represented by a one-phase formation—magma. As the solutions are percolating, the boundaries of all of these zones shift upwards.

Particular interest is presented by phenomena at the melting front. Let us imagine the contact of a granitic magma with a roof of basic rocks. If at this contact only diffusion phenomena were observed, an endo-contact zone of hybrid magma should be formed, which would be in equilibrium with the adjacent metamorphosed rocks. Therefore the solutions separated out by such a magma could not dissolve any of the components of the contact rock. But if the passage of the solutions through the magma and its contacts were similar to the percolation described above, the formation of a hybrid magma would be impeded by a flow of solvents which would dissolve those components, the concentration of which would thus increase along the path of the solvents. Between the magma and the basic roof-rock a sudden increase of activities for a set of components would be established, those components being dissolved and carried upwards by the solution. As a result, the basic rock would be replaced by acid magma, as is often described in the literature. However, the question whether the passage of volatile components through magma can be similar to percolation is still left open.

#### DISCUSSION

M. E. ROUBAULT: Le Professeur Korzhinsky semble expliquer dans l'essentiel la mobilité différentielle des éléments par des différences dans leur solubilités respectives.

Je pense qu'il faut distinguer une tentative d'explication théorique, si intéressants soit elle, de la constatation du fait. Plusieurs auteurs, Professor Holmes et Dr. Doris Reynolds, Tom W. Barth, P. Lapadu-Hargues, R. Perrin et moi-même ont déjà insisté, dans des travaux antérieurs, sur l'importance du déplacement sélectif des éléments. R. Perrin et moi-même avons en outre, insisté sur le fait qu'une telle diffusion fractionnée est un argument important en faveur d'échanges en milieu solide, sans l'intervention d'aucun solvant.

D. S. KORZHINSKY, in reply to Professor Roubault, said that both extreme cases of the migration of matter discussed in his paper—by diffusion and by percolation—and two corresponding types of metasomatic zoning—diffusion-zoning and infiltration-zoning—might take place in principle not only in the presence of aqueous pore-solutions, but also in their absence, that is in the case of migration of matter through a solid crystallized medium. In both cases metasomatic zoning must have been produced, the types and peculiarities of which had been discussed in the paper. Nevertheless, geological evidence encountered in studying deep-seated granite-gneiss complexes, especially the observations of reaction zones at contacts between rocks that were able to interact, allowed him to reach the conclusion that metasomatic phenomena in metamorphism occurred only in rocks which had been soaked by ascending solutions.

As to granite, its formation by metasomatic processes, in particular by diffusion in solid rocks, seemed to him improbable. First of all, such intensive metasomatosis could not have produced rocks with a rich variety of minerals. Theory as well as observations showed that the more intensive the metasomatosis the smaller was the number of minerals in the resulting metasomatic rock. Furthermore, diffusion could not produce the equalization of the quantitative ratio of the minerals of rocks, because the values of chemical potentials of elements did not depend on the quantitative ratio of phases. Therefore, granite with a constant ratio between its minerals could not be produced by metasomatic replacement of rocks of variable composition. Finally, the monotonous composition of granite could hardly be explained other than as a eutectic one.

In many cases granite appeared to have been formed by replacement of a series of sedimentary rocks. But this replacement could not be explained unless an intermediate stage of selective fusion were admitted, i.e. the replacement was not a metasomatic one. The ascending solutions, which caused the fusion, might remove some of the rock components, as was shown in the report.



# ДИФФЕРЕНЦИАЛЬНАЯ ПОДВИЖНОСТЬ КОМПОНЕНТОВ И МЕТАСОМАТИЧЕСКАЯ ЗОНАЛЬНОСТЬ ПРИ МЕТАМОРФИЗМЕ.

Д. С. КОРЖИНСКИЙ

Изучение комплексов метаморфических пород показывает, что метаморфизм, по крайней мере силикатовых пород, всегда совершается при участии восходящих растворов. За это говорит то, что метаморфизм всегда проявляется неравномерно, усиливаясь вдоль некоторых зон и ослабляясь или даже совершенно исчезая в стороне от них, причем усиление метаморфизма (перекристаллизации) всегда сопровождается частичным изменением химического состава пород, т.е. метасоматическими явлениями. Такая неравномерность не может быть объяснена неравномерным распределением температуры, деформации или горной влажности, но указывает на необходимое участие восходящих растворов, которые, насыщая поры пород определенных зон, производили перекристаллизацию пород и изменение их химического состава. В породах, в которых процесс перекристаллизации не завершился, частично разложенные минералы нередко сохраняют обильные микроскопические включения раз'едавшего их раствора. Таковы, например, мутные полевые шпаты, ошибочно описываемые как „пелитизированные.“

Взаимодействие восходящих растворов с горными породами может протекать различно, причем можно различать два крайних типа: 1—раствор поднимается по открытой трещине, напитывая поры боковых пород. Взаимодействие проточного раствора трещины с боковыми породами происходит путем диффузии через неподвижные поровые растворы стенок трещины. Такой „околотрещинный“ метаморфизм особенно характерен для низкотемпературных условий, когда легко образуются трещины, а породы плохо проницаемы для течения растворов. 2—растворы равномерно просачиваются через породы, так что каждое зерно породы непосредственно взаимодействует с текущим раствором, без существенного участия диффузионных процессов. Такой случай характерен для высокотемпературных и среднетемпературных условий, когда горные породы более проницаемы для растворов, а образование трещин затруднено.

В действительности, вероятно, чаще встречается комбинация этих двух предельных случаев или переходы между ними. Прежде всего в зонах просачивания диффузия, вероятно, всегда играет некоторую роль, по крайней мере при замещении внутренних частей зерен, а кроме того просачивание может быть неравномерным, с менее проницаемыми участками с застойными поровыми растворами. Но особое осложнение вносит „фильтрационный эффект“, т.е. возможное отставание растворенного вещества от растворителя при фильтрации, в силу чего растворенное вещество при просачивании не только увлекается растворителем, но отчасти и диффундирует через него. Чем быстрее происходит фильтрация и чем ниже концентрация раствора, тем менее сказывается участие диффузии. С другой стороны, трещины в земной коре редко бывают открытыми и поднятие по ним растворов чаще имеет характер не простого течения, а просачивания, хотя и более быстрого, чем через сплошные горные породы. Тем не менее выделение двух крайних идеальных типов взаимодействия растворов с породами сохраняет свое значение.

Теоретическая интерпретация метаморфизма весьма облегчается естественным допущением, что поровые растворы находятся в химическом равновесии с непосредственно их

включающей горной породой. Наличие химического равновесия в особенности доказывается явлением собирательной перекристаллизации, весьма типичной для метаморфических и метасоматических пород. В силу существования поверхностной энергии, мелкие зерна несколько более растворимы, чем крупные зерна того же минерала. Поэтому одновременно с растворением мелких зерен может происходить рост более крупных, в чем и заключается собирательная перекристаллизация. Раствор при этом находится в равновесии с кристаллами какой то средней величины, т.е. равновесие породы и раствора является очень точным. Наиболее крупные кристаллы образуются при предельно низкой концентрации насыщенного раствора, когда существование мелких и средних зерен невозможно, а потому число кристаллических зерен мало. В частности, рост особо крупных кристаллов часто имеет место в условиях растворения и выноса растворами вещества данных кристаллов, что на первый взгляд кажется парадоксальным. По мере понижения концентрации раствора, растворения мелких кристаллов и уноса их вещества, продолжается рост единичных крупных кристаллов, причем нарастание одних граней иногда сопровождается раз'еданием других; с дальнейшим понижением концентрации раствора наступает растворение и наиболее крупных кристаллов. Так, образование пустот раз'едания, как правило, сопровождается образованием на их стенках друзовых корок крупных кристаллов, как это имеет место в миаролитовых пустотах, хрустальных погребах и альпийских жилах. Обычно полагают, что сначала происходит образование пустоты, а затем рост на ее стенках крупных кристаллов. Однако ряд данных говорит за одновременность этих двух процессов растворения и роста. Такова, например, обычная „присыпка“ на гранях хрусталя (иногда гранях заросших и оказавшихся внутри кристалла) чешуек серицита, хлорита и прочих минералов, освобождающихся при общем растворении вмещающей породы; таковы оторвавшиеся при растворении стенок свободные кристаллы, продолжавшие расти на дне пустоты (Н. Пермаков 1946 г.). Такой же рост крупных кристаллов в условиях их растворения мы видим в метасоматических породах. Так, известные „оспенные“ магнетитовые руды горы Благодати на Урале образуются метасоматически, путем замещения сиенит-порфиров. При этом замещение магнетитом мелкозернистого ортоклазового сиенит-порфира сопровождается ростом единичных крупных кристаллов ортоклаза, которые остаются в виде вкрапленников в магнетитовой массе. При окварцевании различных пород в переходной зоне обычно возникают крупные кристаллы замещаемых минералов породы полевых шпатов или слюды в пегматитах и грейзенах, кальцита в известняках и т.д.

Таким образом, для метасоматических явлений при метаморфизме типична равновесность растворов в отношении вмещающих пород. Недосыщенные растворы, производящие растворение без перекристаллизации, и пересыщенные растворы, из которых могут выпадать коллоиды, проявляются преимущественно в трещинах недалеко от земной поверхности и при выветривании. Для метаморфизма они не характерны.

Если в соприкосновение с горной породой вступает раствор, концентрация которого отличается от равновесной, то между породой и раствором происходит реакция, с образованием в породе „реакционных“ минералов, в состав которых входят как компоненты исходной породы, так и раствора, или же только компоненты породы. При этом изменяются составы как породы, так и раствора, так что они становятся равновесными. В некоторых случаях возможно возникновение нереакционных „осажденных“ минералов, которые целиком выпадают из раствора, не заимствуя компонентов из других минералов. Причиной такого выпадения минерала может служить уменьшение его растворимости, вызванное падением температуры или давления раствора или же изменением состава раствора при растворении других минералов породы. Причиной осаждения может служить также повышение концентрации раствора, вызванное сужением пор по пути следования просачивающихся растворов, т.е. фильтрационным эффектом (Р. А. Мэкей 1946, Д. С. Коржинский 1947).

При метасоматических явлениях окислы и элементы, слагающие горную породу, обна-



руживают независимое поведение. Растворы, воздействуя на породы, не производят заметного перемещения некоторых компонентов, одновременно значительно изменяя состав пород в отношении других компонентов. В этом проявляется „дифференциальная подвижность“ элементов и окислов, имеющая громадное значение не только при метасоматических, но и при магматических процессах. При метасоматическом изменении породы, в силу дифференциальной подвижности ее компонентов, возникает „метасоматическая зональность“, „выражающаяся в одновременном существовании нескольких зон, представляющих разные степени изменения исходной породы. Следует различать „диффузионную метасоматическую зональность“, „характерную для околотрещинного метаморфизма и для реакционных контактовых образований, и „инфильтрационную“ метасоматическую зональность, характерную для зон просачивания. Мы здесь остановимся главным образом на инфильтрационной зональности.

**Инфильтрационная метасоматическая зональность** возникает в силу того, что раствор, по мере проникновения в породу и изменения ее состава, сам тоже изменяется и потому, при дальнейшем просачивании, производит иное изменение породы, чем первоначальное. В силу этого по течению раствора должны возникнуть зоны разного минералогического состава. Предположим, что мы имеем мощную однородную толщу многоминеральной породы. В самую верхнюю зону просочится раствор, настолько изменивший свой состав, в результате взаимодействия с этой породой, что он будет способен производить только простой метаморфизм породы, с изменением содержания воды, но не других компонентов. Наоборот, в самой нижней зоне порода будет полностью переработана воздействием протекающих через нее свежих неизмененных растворов и достигнут полного равновесия с этими растворами. Между этими крайними зонами и расположатся зоны с промежуточной степенью изменения.

Для установления особенностей инфильтрационной зональности мы ограничимся, для простоты, случаем постоянства температуры и внешнего давления для всех зон, однородной пористости (т.е. постоянства коэффициента фильтрационного эффекта) и постоянства состава для каждого из минералов.

В каждой точке, как мы видели, раствор должен находиться в равновесии с вмещающей породой. Это равновесие не нарушается при изменении количественных соотношений минералов, но только при качественном изменении минералогического состава. Поэтому реакция просачивающегося раствора с породой может иметь место только на границе двух зон разного минералогического состава, в пределах же каждой зоны никакого взаимодействия не происходит. При однородном исходном материале, каждая зона имеет постоянный минералогический состав.

Количество  $dm$  растворенного компонента **a**, которое переносится просачивающимся раствором через любое поперечное к нему сечение, равно произведению объема  $dv$  этого раствора на концентрацию  $c_a$  в нем данного компонента и на коэффициент  $\varphi_a$  фильтрационного эффекта (коэффициент увлекаемости растворителем) для данного компонента в данной среде, т.е.:

$$dm = \varphi_a \cdot c_a \cdot dv$$

При свободном течении раствора, когда растворенное вещество полностью увлекается течением раствора, коэффициент  $\varphi_a$  равен единице. В случае, если среда пропускает растворитель, но полностью задерживает данный растворенный в ней компонент, этот коэффициент был бы равен нулю. Фильтрационный эффект вызывается различием средней скорости движения частиц растворителя и растворенного вещества в пористой среде, а не явлениями адсорбции. Величина фильтрационного эффекта при фильтрации через горные породы, особенно для высоких температур, не известна, но несомненно, что коэффициент может сильно отличаться от единицы. Но в данном случае этот коэффициент введен только для полноты, так как метасоматическая зональность может возникать и независимо от наличия фильтрационного эффекта.

Рассмотрим теперь контакт между двумя метасоматическими зонами I и II, с раствором, просачивающимся по направлению от зоны II к зоне I. Содержание компонента а на единицу объема в зоне I обозначим  $a^I$ , а в зоне II —  $a^{II}$ . Концентрацию этого компонента в растворе в пределах зоны I обозначим  $c_a^I$ , тоже для зоны II —  $c_a^{II}$ . Элементарный объем раствора  $dv$ , просочившийся через единицу поверхности контакта, принесет со стороны зоны II к месту реакции компонент а в количестве:  $\varphi_a \cdot c_a^{II} \cdot dv$ , а унесет в сторону зоны I —  $\varphi_a \cdot c_a^I \cdot dv$ . В результате прохождения этого элементарного объема раствора контакт зон пусть переместится на расстояние  $dx$ . Если замещение не сопровождается изменением объема, как это обычно принимается, то должно иметь место равенство:

$$\varphi_a (c_a^I - c_a^{II}) \cdot dv = (a^I - a^{II}) dx$$

Отсюда получаем отношение скорости перемещения границы двух зон к скорости просачивания:

$$\frac{dx}{dv} = \varphi_a \frac{c_a^I - c_a^{II}}{a^I - a^{II}}$$

Аналогичное выражение можем получить для каждого из компонентов. Так как во всех таких выражениях дело идет о скорости перемещения одной и той же границы, то получим:

$$\frac{dx}{dv} = \varphi_a \frac{c_a^I - c_a^{II}}{a^I - a^{II}} = \varphi_b \frac{c_b^I - c_b^{II}}{b^I - b^{II}} = \varphi_d \frac{c_d^I - c_d^{II}}{d^I - d^{II}} = \dots$$

Если при замещении породы I породой II объем возрастает в  $r$  раз, то мы получили бы:

$$\frac{dx}{dv} = \varphi_a \frac{c_a^I - c_a^{II}}{a^I - ra^{II}} = \varphi_b \frac{c_b^I - c_b^{II}}{b^I - rb^{II}} = \varphi_d \frac{c_d^I - c_d^{II}}{d^I - d^{II}} = \dots$$

Таким образом, получаем  $n-1$  уравнение, связывающее величины содержаний и концентраций  $n$  компонентов в двух соседних зонах. Уже самый факт существования этих уравнений дает нам возможность сделать некоторые выводы о числе минералов в метасоматических зонах.

При постоянных температуре и внешнем давлении, состояние равновесной минеральной системы из  $n$  компонентов определяется  $n$  независимыми факторами, которые задаются внешними условиями. Каждый компонент вносит один независимый фактор равновесия. Для менее растворимых („инертных“) компонентов независимым фактором будет их содержание в породе, зависящее от исходного состава. Для других („вполне подвижных“) компонентов независимым фактором является их активность во внешней среде или концентрация в притекающем растворе. Если образующиеся минералы не допускают вариаций состава, то число сосуществующих минералов в породе равно числу компонентов с независимо заданным содержанием (т.е. числу „инертных“ компонентов). Число „подвижных“ компонентов, с независимо заданной активностью, равно разности между числом компонентов и числом минералов (подробности см. в другом докладе автора данному Конгрессу).

Сопоставим две соседние зоны фильтрационной колонны. В первой, верхней зоне, исходный состав породы, за исключением содержания воды, еще не успел измениться. Содержания всех компонентов (если исключить воду из числа компонентов) независимо заданы исходным составом породы и потому число  $p$  возникших при метаморфизме минералов должно быть равно числу компонентов ( $p=n$ ). В примыкающей второй зоне, возникшей за счет воздействия растворов на первую, состояние породы будет определяться как составом исходной породы, так и концентрацией воздействующих растворов. Но мы видели, что существует  $n-1$  уравнение, связывающее величины содержаний и концентраций компонентов в двух соседних зонах. Поэтому из  $n$  независимых параметров, определяющих состояние породы во второй зоне, только один может быть задан концентрацией раствора (концентрацией наиболее подвижного компонента), а остальные через посредство  $n-1$  уравнения определя-



ются содержанием компонентов в первой зоне. В силу наличия одной независимо заданной концентрации, число минералов во второй зоне уменьшится на единицу, т.е. будет равно  $(n-1)$ .

В третьей зоне параметры состояния при помощи тех же  $n-1$  уравнений связываются не только с содержанием компонентов во второй зоне, но и с одной независимой концентрацией подвижного компонента этой второй зоны. Поэтому в третьей зоне уже два компонента могут иметь независимую концентрацию, т.е. быть подвижны, а число минералов может уменьшиться еще на один. Таким образом, при каждом переходе к более нижней зоне число инертных компонентов и число минералов уменьшается на единицу, а число подвижных компонентов соответственно возрастает. В частном случае, когда при определенной концентрации подвижного компонента возможно превращение одной минеральной ассоциации в другую без уменьшения числа минералов, в прилежащих зонах может оказаться равное число минералов и инертных компонентов. В самой нижней, наиболее измененной зоне число реакционных минералов может спуститься до единицы, или даже до нуля, в случае если все компоненты исходной породы вынесены и порода полностью замещена осажденным минералом.

Ряд особенностей инфильтрационной зональности можно предвидеть, основываясь на приведенной выше скорости продвижения границ зон, приняв во внимание, что скорость передвижения для каждой более верхней зоны должна быть больше, чем нижней. Главнейшие особенности этой зональности следующие: 1) При воздействии просачивающихся растворов на многокомпонентную породу должен возникнуть ряд резко отграниченных метасоматических зон, которые будут разрастаться одновременно, с наступлением нижних на верхний. 2) Замещение происходит только на границе зон. В пределах зон возможно лишь изменение состава переменных минералов. 3) В каждой зоне можно различать „инертные“ компоненты, содержание которых определяется содержанием в исходной породе, и „подвижные“ компоненты, содержание которых зависит от соотношения инертных и от концентрации раствора, но не от первичного их содержания. Число минералов равно числу инертных компонентов. Поэтому выводы об инертном или подвижном поведении компонентов при метасоматозе должны подтверждаться сопоставлением числа компонентов и числа минералов. 4) От верхней к нижней зоне число инертных компонентов и число минералов постепенно уменьшается, а число подвижных компонентов соответственно возрастает. 5) Чем выше растворимость компонента и способность его просачиваться с растворителем, тем скорее переходит он в подвижное состояние: сохраняют инертность вплоть до нижних зон наименее растворимые, т.е. наименее подвижные компоненты. 6) На границе двух зон, в связи с реакциями замещения, концентрация просачивающегося раствора резко меняется. В силу равновесия между породой и раствором, соприкасающиеся породы двух зон должны обладать различной активностью компонентов, т.е. не будут находиться в химическом равновесии. В силу этого могут отсутствовать некоторые зоны, которые образовались бы как переходные между данными при диффузионном взаимодействии. 7) Растворение и вынос части компонентов какого либо минерала должно привести, согласно закона действия масс, к повышению активности остающихся компонентов этого минерала. Если растворяются и выносятся все компоненты какого либо минерала, то над зоной полного выноса может образоваться зона, обогащенная наименее подвижным компонентом этого минерала. Так, в местах грейзенизации и последующего окварцевания полевошпатовых пород встречаются обогащенные глиноземом грейзены. Богатые глиноземом серицитовые, андалузитовые и корундовые породы, встречающиеся среди окварцованных кислых эффузивов, вероятно имеют сходное происхождение.

До сих пор мы имели в виду только реакционные минералы, т.е. содержащие компоненты исходной породы. Но, кроме того, раствор может отлагать некоторые свои компоненты в виде самостоятельных „осажденных“ минералов. Это может происходить в силу изменения

состава раствора по мере проникновения в породу, благодаря возможному влиянию концентрации одним компонентов на растворимость других. В таком случае осаждение минерала должна быть приурочено к определенным зонам, причем характер и количество отлагающегося минерала должны зависеть не только от состава раствора, но и от состава породы. Такая „избирательность“ замещения подтверждается наблюдениями. Наблюдения показывают далее, что при всех постмагматических процессах, вплоть до наиболее высокотемпературных, одновременно осаждается только по одному минералу, что нередко приводит к образованию мономинеральных пород. Последнее имеет место при окварцевании пород, при образовании некоторых метасоматических сульфидных руд и высокотемпературных магнетитовых руд. Автор не встречался со случаями, когда бы при метасоматозе осаждалось одновременно более одного минерала. Однако, теоретическая сторона этого вопроса неясна и возможно, что при известных условиях может осаждаться более одного минерала одновременно, но тогда количественное соотношение этих минералов должно зависеть от состава замещаемой породы.

**Диффузионная метасоматическая зональность** возникает в тех случаях, когда замещение обусловлено диффузионным обменом компонентов. Отчетливое ее проявление мы видим при околотрещинном метасоматозе, когда поднимающийся по трещине раствор пропитывает боковые породы. Взаимодействие проточного раствора трещины с боковой породой осуществляется при помощи встречной диффузии компонентов через застойные поровые растворы. При этом возникает несколько резко отграниченных реакционных зон, подобных таковым при инфильтрационной зональности. В самой внешней зоне воздействие растворов приводит к простому метаморфизму без изменения состава, кроме воды. В каждой более внутренней зоне все большее число компонентов переходит в подвижное состояние, с соответственным уменьшением числа минералов, вплоть до внутренней, обычно мономинеральной зоны, примыкающей к мономинеральному жильному выполнению. Все эти зоны разрастаются одновременно, с замещением внешних внутренними. Такие околосильные зоны достигают нескольких метров мощности. Теория такой зональности рассмотрена автором в другом месте.

Более сложен случай реакционных метасоматических образований на контактах химически неравновесных пород. Описанию и теоретическому анализу таких образований посвящен ряд работ автора. Так, при высокотемпературном метаморфизме на небольших глубинах между известняками и силикатовыми породами возникают скарновые зоны. Общеизвестны реакционные зоны между гипербазитами и кислыми породами. В условиях больших глубин реакция между доломитами и алюмосиликатовыми породами приводит к образованию флогопитовых и лазуритовых месторождений. Характерно, что даже в интенсивно метаморфизованных гнейсовых комплексах такое взаимодействие проявляется крайне неравномерно. В то время как в отдельных участках контакта мощность зоны взаимодействия достигает нескольких метров (метров до 20 в исключительных случаях), в других местах того же контакта она спускается до нескольких миллиметров или менее. Такая неравномерность доказывает, что взаимодействие пород могло совершаться только в местах воздействия восходящих растворов, питавших поры пород. Диффузия, таким образом, совершалась через поровые растворы, а не через твердое вещество. Участие восходящих растворов подтверждается также тем, что усиление взаимодействия всегда сопровождается привносом или выносом более подвижных компонентов (например, привносом железа и магния в скарновых зонах). Кроме того известно, что взаимодействие пород резко усиливается вдоль трещин, так что трещины, пересекающие контакт взаимодействующих пород, превращаются в метасоматические жилы—например просечки лазуритовых пород в пегматитах среди доломитов, флогопитовые и скарновые жилы. Упомянутые примеры взаимодействия все относятся к постмагматическим, но весьма высокотемпературным явлениям; последнее видно из образования таких метасоматических минералов, как всех плагиоклазов,



вплоть до анортита, гранатов, форстерита, шпинели, лазурита, гаюина, нефелина, санидинового ортоклаза и проч.

Таким образом, метасоматическое взаимодействие пород совершается в зонах просачивания восходящих растворов, в условиях вполне подвижного поведения ряда более подвижных компонентов (в особенности углекислоты и щелочных металлов, иногда также магния, железа и других). Через эти восходящие растворы, если они просачиваются в зоне контакта способных к реакции пород, происходит диффузионный обмен менее подвижных компонентов, к каковым при образовании скарнов относится кальций, кремнезем и глинозем. Такое сложное взаимодействие двух пород и раствора может быть названо биметасоматозом. Реагирующие породы разделяются несколькими резко ограниченными зонами с малым числом минералов, вплоть до мономинеральных зон (мономинеральные гранатовые, пироксеновые, флогопитовые, жадеитовые, нефритовые, тальковые и прочие породы). Малая подвижность глинозема сравнительно с кремнеземом приводит к очень характерной для биметасоматоза метасоматической десиликации. Вынос кремнезема в сочетании с уменьшением объема алюмосиликатовой породы, при этом, приводит к резкому повышению содержания глинозема в некоторых разностях.

Диффузионное взаимодействие могло иметь место также между жидкой магмой и боковой породой. Большое значение такому взаимодействию придавал А. Е. Ферсман, детально описавший встречную миграцию элементов в изумрудных копях Урала (1925).

Исследования в гнейсовых докембрийских комплексах Сибири показывают, что очень часто граниты и пегматиты дают непосредственные контакты даже с доломитами без образования реакционных зон. Такие зоны развиваются лишь местами уже после кристаллизации гранитов и пегматитов, при воздействии постмагматических растворов.

Диффузионное перемещение компонента возможно только при наличии градиента его активности (концентрации в растворе). С точки зрения правила фаз, концентрация диффундирующих подвижных компонентов обладает степенью свободы и потому переход каждого из компонентов в подвижное состояние сопровождается уменьшением на единицу числа минералов. Уменьшение числа минералов является необходимым признаком как диффузионного, так и инфильтрационного перемещения вещества. В этом заключается сходство инфильтрационной и диффузионной метасоматической зональности. Отличием является то, что диффузионные метасоматические зоны, как правило, состоят из одних реакционных минералов. Осаждение раствором более растворимых минералов имеет место только в трещинах и в тех породах, замещение которых сопровождается уменьшением объема, т.е. падением давления, причем как при инфильтрации одновременно выпадает лишь один из минералов. Резкие границы между зонами типичны для всякой метасоматической зональности поскольку они не нарушаются влиянием неоднородной трещиноватости и пористости.

Хотя автор специально вопросами гранитизации не занимался, уместно будет попутно высказаться по этому дискуссионному вопросу. Многие авторы (среди русских геологов особенно Н. Г. Судовиков) в настоящее время высказываются за метасоматическое образование гранитов за счет гранитизации других пород. Автор полагает, что полиминеральность гранитов и устойчивость их количественного минералогического состава противоречат метасоматическому их происхождению и не могут быть объяснены без посредства расплавления, т.е. магматической стадии. Диффузия компонентов через растворы или через твердые породы не может вызвать выравнивания количественных соотношений минералов. Представление об исключительной роли диффузии через твердые породы при метаморфизме противоречит геологическим наблюдениям над биметасоматическими образованиями, как указано выше, и вообще над распределением метаморфизма и диффузионной зональности.

Значительно больше оснований имеется для того, чтобы связывать метаморфизм и гранитизацию с воздействием просачивающихся растворов, как это предполагалось П. Термье (1910). Ювенильные восходящие растворы существенно водные, просачиваясь через

сиалическую оболочку земного шара, могут вызвать избирательное ее расплавление, с образованием эвтектической гранитной магмы. Существенная часть ювенильных летучих компонентов удерживается образующейся магмой и выделяется только при ее кристаллизации, что обуславливает особую интенсивность постмагматического метаморфизма. Другая часть диффундирует через магму, а затем просачивается через породы кровли, производя их метаморфизм и гранитизацию. При этом должна возникнуть инфильтрационная метасоматическая зональность, свойства которой рассмотрены выше. Вверху растворы производят „нормальный метаморфизм“, при котором только вода и углекислота ведут себя подвижно. Ниже идет зона, в которой активность калия и натрия приведены к уровню, установившемуся в подлежащей гранитной магме, с соответствующим уменьшением максимального числа сосуществующих минералов. Поэтому, с повышением температуры метаморфизм этой зоны приобретает характер гранитизации, особенно вблизи контактов с гранитами, где начинается избирательное плавление. Самая нижняя зона представлена однофазным образованием — магмой. По мере просачивания растворов границы всех этих зон продвигаются вверх.

Особый интерес представляют явления на фронте расплавления. Представим контакт гранитной магмы с кровлей пород основного состава. Если в этом контакте имеют место только диффузионные явления, то должна образоваться эндоконтактная зона гибридной магмы, равновесной с прилежащими метаморфизованными породами. Поэтому растворы, выделяемые такой магмой, не смогут растворять каких либо компонентов контактовой породы. Но если прохождение растворов через магму и ее контакты сходно с вышеописанным просачиванием, то образование гибридной магмы будет затруднено током растворителей, которые должны растворять те компоненты, концентрация которых по пути растворителей повышается. Между магмой и основной породой кровли установится скачок активностей для ряда компонентов, которые и будут растворяться и увлекаться раствором вверх. В результате основная порода будет замещаться кислой магмой, как это часто описывается в литературе. Но конечно, остается открытым вопрос о том, может ли прохождение летучих компонентов через магму быть сходным с просачиванием.



# METAMORFISMO SELETTIVO E PROCESSI METASOMATICI DI CONTATTO NEL MASSICCIO DELL'ADAMELLO

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## ABSTRACT

Il plutone recente (terziario) dell'Adamello, nelle Alpi Centrali italiane, è costituito in prevalenza da una massa granodioritico-tonalitica, che qua e là, specialmente alla periferia, presenta limitate concentrazioni femiche ed ultrafemiche e un ricco seguito di filoni variamente differenziati. Il massiccio eruttivo viene a diretto contatto con formazioni sedimentarie e scistoso-cristalline diversissime per età geologica e per composizione petrografica (dalle filladi e dai paragneiss del Cristallino antico alle arenarie del Permiano, dalle fini arenarie e dolomie cariate del Trias inferiore alla complessa successione di rocce calcareo-marnose, arenacee e dolomitiche del Trias medio e superiore). Ne risulta un'ampia gamma di manifestazioni metamorfiche di contatto con svariati effetti selettivi, talvolta senza sensibile migrazione di materia, talaltra invece con evidente apporto di sostanze magmatiche e conseguenti processi metasomatici nelle rocce incassanti.

La nota che presentiamo riassume il risultato di parecchi anni di ricerche da parte nostra e dei nostri allievi delle Scuole di Mineralogia e Geologia dell'Università di Padova: ricerche che si concluderanno prossimamente in una esauriente monografia geologico-petrografica sull'intero massiccio dell'Adamello.

IL massiccio intrusivo dell'Adamello, che forma oggetto della presente nota, si trova nelle Alpi Meridionali a cavallo fra la Lombardia e il Trentino, a sud del Passo del Tonale. Esso è costituito essenzialmente da una cospicua massa granodioritico-tonalitica di età terziaria, che è compresa entro formazioni scistose del Cristallino antico e terreni permotriassici di svariata composizione.

Questo imponente massiccio alpino è già stato oggetto, fra la fine del secolo scorso e l'inizio di questo, di una fondamentale monografia geologica da parte di W. Salomon e di vari importanti lavori di C. Riva, G. B. Trener, H. P. Cornelius, M. Furlani ed altri autori. Tuttavia questo ciclo di ricerche non ha esaurito lo studio geologico-petrografico dell'Adamello e molto è rimasto ancora da fare: sia per quanto riguarda il rilevamento geologico di dettaglio e l'esame approfondito delle condizioni tettoniche; sia per quanto si riferisce alle indagini sulla differenziazione chimico-petrografica della massa magmatica e sui complessi fenomeni metamorfici di contatto.

In questo intento già da vari anni, assieme ad alcuni nostri allievi e collaboratori, abbiamo iniziato un nuovo ciclo di ricerche geologiche e petrografiche di dettaglio, alcune delle quali già pubblicate e numerose altre in corso di esecuzione (v. *Bibliografia*). A conclusione di tali studi, contiamo di poter presto pubblicare una monografia sintetica di carattere moderno su questo interessante plutone, che assume tanta importanza nel quadro della geologia alpina.

## LA MASSA INTRUSIVA E LE SUE DIFFERENZIAZIONI

Accenniamo qui brevemente alle caratteristiche essenziali della massa magmatica e delle sue differenziazioni, quali risultano dai lavori elencati nella Bibliografia e da un complesso di oltre sessanta analisi chimiche eseguite in quest'ultimo decennio.

Le facies più caratteristiche del plutone sono le seguenti:

(a) *granodiorite biotitica* a grana media o medio-minuta, che predomina nella parte centrale del massiccio, costituendo le cime più elevate del gruppo dell'Adamello, e affiora altresì su larghe aree verso il margine settentrionale (per es.: val d'Avio e valle del Pisgana) e verso l'estremità nord-orientale.

(b) *tonalite biotitico—anfibolica a grana medio—grossa* con plagioclasio andesinico—labradoritico fortemente zonato e con una certa tendenza porfirica per l'idiomorfismo dei vistosi cristalli di orneblenda (= “tonalite tipo Adamello” di Trener). Questa bella roccia, con chimismo intermedio fra i tipi “tonalitico” e “leucotonalitico” di Niggli, prevale nel gruppo della Presanella, sul fianco destro della val Nambrone, sul versante sinistro dell'alta e media val di Genova e in tutte le alte valli che irradiano a ovest, sud e sud—est dall'acrocoro centrale dell'Adamello (Baitone-Miller, Salarno, Adamè, Fumo, Cavento-Valletta ecc.).

(c) *tonalite biotitico—anfibolica a grana più minuta* (= “tonalite tipo Monte Re di Castello” di Trener), che si sviluppa nella Valle di Daone, nel gruppo del M. Re di Castello e nei contrafforti meridionali del massiccio, dove offre transizione verso facies leucotonalitiche (lago della Vacca) e granodioritiche (M. Bruffione, M. Laione, val Fredda, val Cadino).

(d) *nuclei granito—granodioritici marginali* del Corno Alto—Sostino, Sabion, Madonna di Campiglio, Meledrio—Spolverin ecc. sul lato orientale e nord—orientale del plutone. Queste masse periferiche a tendenza sialica presentano una certa individualità geologica, che consiglia a tenerle distinte da analoghe facies del corpo principale del plutone.

(e) *zolle di concentrazione femica.*—La zona più ricca di differenziazioni basiche di varia composizione è quella che trovasi al margine meridionale dell'Adamello e precisamente nella zona compresa fra la Val Stabio e l'alta valle del Caffaro, ove si notano: il nucleo dioritico del M. Costone; la diorite del lago Frerone; la massa dioritica e gabbrodioritica del M. Blumone; la complessa area basica del M. Cadino, costituita da innumerevoli lenti e zolle dioritiche e gabbrodioritiche disseminate in una massa di fondo granitica; e infine la massa gabbrica anfibolico—pirossenica del M. Mattoni, che presenta nuclei ultrafemici di orneblendite e geodi pegmatitiche a grandi cristalli allungati di anfibolo.

Altre facies basiche, di prevalente composizione dioritico—anfibolica, si trovano sul fianco destro della val di Daone, a nord del lago di Campo, nonché alla Bocca della Cunella fra la valle di S. Valentino e l'alta val Breguzzo e, inoltre, presso Cima Agosta e Cima Uzza.

Nuclei dioritico—anfibolici affiorano pure fra gli scisti cristallini al margine nord—occidentale della massa tonalitica, sul fianco sinistro della Valcamonica (M. Marser—val Malga, conca del Baitone, val Moja ecc.).

Mentre le facies basiche finora ricordate si possono considerare essenzialmente come differenziazioni periferiche del plutone, altri minori nuclei femici si trovano sparsi nell'interno della massa eruttiva principale e sono costituiti per lo più da concentrazioni biotitiche nella granodiorite (val d'Avio) e da concentrazioni anfiboliche o anfibolico—biotitiche nella tonalite (Pantano d'Avio, alte valli di Miller, Salarno e Adamè, zona lago Nero—rifugio Mandrone nell'alta valle di Genova). Queste rocce sono caratterizzate da un netto idiomorfismo dei cristalli di orneblenda verde ad abito prismatico tozzo e della biotite a lunghe pile di lamelle sovrapposte.

(f) *filoni.*—La massa eruttiva principale è accompagnata da un ricco seguito filoniano, che si sviluppa soprattutto alla periferia del massiccio e nelle formazioni circostanti. La zona più ricca di filoni è quella del settore meridionale fra la valle di Stabio e l'alta vallè del Caffaro, già ricordata per la varietà delle segregazioni basiche. In quest'area relativamente ristretta si possono contare oltre trecento filoni poco differenziati (graniti, microdioriti, malchiti e porfiriti plagioclasiche), o nettamente differenziati sia in senso sialico (apliti e quarziti feldispatiche) sia in senso femico (porfiriti orneblendiche, spessartiti anfiboliche, kersantiti anfibolico—biotitiche, porfiriti anfibolico—pirosseniche talora con olivina).

Fra le altre zone notevoli per numero e varietà di filoni possiamo citare: il gruppo del M. Re di Castello con il bacino del lago di Campo; il gruppo del Corno Alto e la regione fra la val Seniciaga e la val di Borzago; il nucleo periferico del Doss del Sabion, ove sono frequenti facies aplitiche tanto filoniane quanto marginali del corpo granodioritico; l'alta val di Genova nei dintorni del rifugio e del ghiacciaio del Mandrone.



Piuttosto rare appaiono le pegmatiti, che tuttavia si possono qua e là osservare specialmente nelle valli di Genova, di Salarno e dell'Adamè.

Un motivo strutturale di notevole interesse è costituito dagli orientamenti paralleli di origine primaria, fluidale, che presenta la massa eruttiva lungo i margini del settore nord—orientale, sia in val di Sole sia in val Rendena, come pure nella bassa val di Genova ove il fenomeno assume una particolare intensità ed evidenza. La tessitura parallela si ritrova anche nell'alta val Borzago e ancora più a sud in val Cadino.

La nuova serie di numerose analisi chimiche che abbiamo ormai a disposizione (eseguite da A. Bianchi, A. Cavinato, D. Colbertaldo, G. De Lucchi, M. Fenoglio, O. Hieke, R. Malaroda, G. Ogniben, G. Schiavinato), consente di riconoscere nella massa e nei suoi filoni un chimismo essenzialmente alcali—calcico, con lievi e locali deviazioni in senso alcalino.

#### LE FORMAZIONI INCASSANTI

Il plutone dell'Adamello si è intruso in una potente serie di terreni che si estende dal Cristallino antico al Trias superiore, comprendendo i seguenti termini stratigrafici (dal basso in alto):

(1) *Cristallino antico* prepermiano, verosimilmente archeozoico: filladi quarzifere, quarziti sedimentogene, micascisti, paragneiss e scisti carboniosi della serie sudalpina; ortogneiss di Stavel, micascisti, paragneiss e altre rocce della serie austroalpina del Tonale.

(2) *Permiano*: arenarie minute, passanti ad argilloscisti finemente stratificati, di colore grigio o verdastro e qualche volta anche rossastro (stati di Collio); porfidi quarziferi e tufi, talora in facies laminata; arenarie di Gardena, per lo più rossastre, con letti di conglomerati a facies del " Verrucano "; calcare a *Bellerophon* (dove presente).

(3) *Scitico (Werfeniano) inferiore*: arenarie minute e argille scistose rosse del Servino, talora con intercalazioni calcaree.

(4) *Scitico (Werfeniano) superiore*: calcare a cellette e dolomia cariata.

(5) *Anisico inferiore*: dolomie (facies di scogliera); calcari scuri, finemente stratificati, nodulosi—lenticolari, in fittissima alternanza con sottili letti argilloso—marnosi (facies camuna); grossi banchi calcarei, compatti, chiari e scuri, a superfici piane, senza letti marnosi e argillosi (facies giudicariense).

(6) *Anisico superiore*: calcari nerastrati in fitta e regolare alternanza con letti marnosi, talora intercalati da banchi arenacei e conglomeratici.

(7) *Ladinico inferiore* (strati di Livinallongo — Buchenstein, zona a *Protrachyceras reitzi*): calcari nodulari scuri più o meno ricchi di lenti selciose e a sottili interstratificazioni argillose, che talora alternano con materiali tufacei, scuri o verdastri (pietra verde); i calcari nodulari possono localmente far passaggio a banchi selciosi con arnioni e letti calcarei.

(8) *Ladinico superiore* (strati di La Valle — Wengen, zona a *Daonella lommeli*): calcari finemente stratificati, marne e argilloscisti, per lo più di colore scuro fino a nero, tufi e arenarie tufacee.

(9) *Ladinico* (facies eteropica di scogliera): dolomie e calcari di Esino.

(10) *Carnico inferiore* (strati di S. Cassiano): dolomia cariata, giallastra, farinosa presso la vetta del M. Frerone nell'Adamello meridionale.

(11) *Carnico superiore* (strati di Raibl): nell'area interessata dall'intrusione il Raibiano sembra rappresentato da originari scisti arenaceo—argillosi alternanti con arenarie minute, quali si osservano in facies fortemente metamorfica per contatto sul valico del Forcel Rosso, a cavallo fra la valle di Adamè e l'alta valle del Chiese.

(12) *Norico*: dolomie e calcari dolomitici (dolomia principale).

(13) *Retico inferiore*: calcari nerastrati con sottili letti marnosi (in facies metamorfica per contatto sul fianco destro della val di Fumo, presso Malga Breguzzo).

(14) *Retico superiore e Lias* (?): al disopra dei calcari marnosi retici segue, in val di Fumo, una potente massa calcareo—dolomitica che rappresenta la parte alta del Retico e forse anche il Lias inferiore (dolomia a *Conchodon*).

Per quanto riguarda la distribuzione geologico—topografica dei terreni suelencati, che vengono

a diretto contatto con la massa intrusiva, ci limitiamo a dare qui alcuni cenni necessari per la comprensione dei processi metamorfici di cui diremo in seguito.

Al margine settentrionale il plutone è direttamente incassato nella serie delle filladi quarzifere sudalpine e rocce associate ("scisti di Edolo" del Salomon) e soltanto all'estremità nord—orientale, in val di Sole, raggiunge gli scisti della serie austroalpina del Tonale.

I parascisti di Edolo, fasciati da una sottile copertura di terreni permo—triassici in corrispondenza alla grande anticlinale camuna, prevalgono pure sul lato occidentale fra Edolo e Capodiponte in Valcamonica. Più a sud fin oltre Breno e su tutto il settore meridionale, dalla Valcamonica alla valle delle Giudicarie, la massa eruttiva è contornata da vari termini della serie triassica sudalpina, a cui si accompagnano verso l'esterno le formazioni permiane.

Sul lato orientale, in val Rendena, prevalgono parascisti di varia composizione (filladi, quarziti, micascisti, paragneiss), che il Salomon ha riunito sotto la denominazione complessiva di "scisti di Rendena." Dobbiamo aggiungere però che in tutto il settore da Pinzolo a Madonna di Campiglio e a Dimaro gli originari rapporti intrusivi fra la massa magmatica e le formazioni incassanti sono mascherati o addirittura sostituiti da nuovi contatti di natura tettonica, che hanno addossato al margine nord—orientale del massiccio, oltre alle formazioni del Cristallino antico e del Trias superiore, anche terreni cretaceo—eocenici.

In conseguenza di queste dislocazioni, la massa tonalitica—granodioritica e le rocce incassanti appaiono qui intensamente deformate e ridotte allo stato di cataclasiti e miloniti post—cristalline, che formano oggetto di una interessante memoria del Dott. R. Malaroda. Fenomeni analoghi si osservano anche lungo l'orlo settentrionale del plutone, sul fianco destro della val di Sole, in rapporto alla vicinanza della linea tettonica del Tonale (= linea insubrica *auct.*).

#### FENOMENI METAMORFICI DI CONTATTO E LORO EFFETTI SELETTIVI

La varia composizione della massa magmatica e dei suoi filoni e soprattutto la grande diversità dei terreni che costituiscono la ricca serie stratigrafica della regione, hanno dato luogo a una vastissima gamma di fenomeni metamorfici di contatto, che compongono un quadro di effetti selettivi di rara complessità e del più grande interesse.

Per il breve spazio accordato alla presente nota, non possiamo che limitarci a cogliere qua e là qualche motivo più saliente di queste multiformi azioni metamorfiche, che erano poco o nulla conosciute fino al tempo dei nostri studi sulla regione di Bazena, ove nel 1937 abbiamo guidato numerosi geologi italiani e stranieri in occasione della 50ª adunanza estiva della Società Geologica Italiana.

(a) *Facies metamorfiche di contatto negli scisti cristallini.*—Avvicinandosi alla massa eruttiva, le filladi quarzifere e i micascisti della Valcamonica come pure i parascisti della val Rendena appaiono sempre più intensamente induriti, silicizzati, e acquistano una cristallinità più spiccata assumendo una caratteristica tinta bruno—rugginosa a riflessi violacei per la diffusa e abbondante neogenerazione di biotite. Qua e là fanno passaggio a cornubianiti gneissiche contenenti minerali caratteristici di contatto, come andalusite, sillimanite, cordierite, granato, tormalina ecc. Fra le zone ove questi effetti si osservano su più vasta scala o con maggior intensità possiamo citare: la bassa val d'Avio, la conca del lago Baitone, l'alta Valsaviore, i gruppi del Corno Alto e del M. Sabion.

(b) *Facies metamorfiche nei terreni permiani.*—In tutta la formazione permiana che si estende a margine della tonalite tipo M. Re di Castello, dal lago d'Arno al lago di Campo, l'influenza di contatto della massa magmatica si manifesta in modo vistoso per la caratteristica e diffusa macchiatura, rappresentata da chiazze, efflorescenze dendritiche, mosche e lenticelle di tinta grigio—bruna o grigio-verdastra. Si tratta di quarziti e di cornubianiti quarzoso—feldispatiche, a biotite, clorite, muscovite e tormalina eterogeneamente distribuite. In modo analogo, i fenomeni metamorfici hanno trasformato le primitive arenarie permiane di Gardena in quarziti macchiettate anche al M. Ignaga e al passo del Bos, sui due lati del vallone dell'Adamè.

(c) *Facies metamorfiche nei sedimenti del Trias inferiore (Scitico).*—La complessa successione di terreni che formano la parte bassa del Trias inferiore, già costituita originariamente da arenarie



minute e argille scistose con intercalazioni calcareo—marnose, è stata trasformata essenzialmente in una ripetuta e fitta alternanza di cornubianiti e scisti cornubianitici variegati, a liste o a chiazze bruno—rossastre, grigie e verdi, nelle quali prevalgono talora la biotite e talora la fassaite come prodotti di neoformazione, accompagnate qua o là da tormalina, andalusite, sillimanite, flogopite, granato.

Con i materiali sopradetti alternano banchi sottili di marmi saccaroidi e calcefiri a granati, pirosseni, flogopite, epidoto e altri silicati. Le zone più interessanti per la constatazione sul terreno di questi eleganti prodotti del metamorfismo sono la sponda destra del lago d'Arno, il passo di Campo e l'alto valico del Forcel Rosso fra la val di Fumo e la valle dell'Adamè.

Nelle stesse zone si può inoltre osservare lo scarso effetto risentito dalla dolomia cariata (parte alta del Trias inferiore), che tutt'al più assume una grana saccaroide senza acquistare di solito nè compattezza litoide nè minerali di nuova genesi, cosicchè rimane facilmente erodibile anche nelle zone di intenso metamorfismo.

(d) *Facies metamorfiche nei terreni anisici.*—La regione di Bazena, nell'Adamello meridionale, è senza dubbio quella che offre il maggior interesse per lo studio dei vistosi effetti selettivi di metamorfismo sui sedimenti calcarei, calcareo—dolomitici e calcareo—marnosi con qualche letto arenaceo, dell'Anisico.

La Valbona, l'alta Valfredda e le pareti meridionale e orientale del M. Frerone rivelano su larga scala la profonda trasformazione subita dai terreni dell'Anisico inferiore in facies camuna. Mentre i letti calcarei presentano essenzialmente un semplice processo di ricristallizzazione e sono in generale poveri di minerali nuovi (fra i quali possiamo annoverare flogopite, tremolite e rara scapolite), invece negli interstrati marnosi si sviluppano calcefiri e cornubianiti a granato, fassaite, epidoto e flogopite con vario gioco di associazioni e di aspetti.

Per la facies prevalentemente calcarea, giudicariense, dell'Anisico inferiore, possiamo assumere come tipico il giacimento da noi rilevato lungo la strada carrozzabile presso Alpe Bazena, dove un grosso filone granodioritico—dioritico viene a contatto con i predetti terreni sedimentari, inviando in essi alcune vene aplitiche. Il giacimento fu studiato in particolare da G. Schiavinato, il quale vi riconobbe la presenza di “ skarn ” andraditico—hedenbergitici a plagioclasio di origine pneumatolitico—metasomatica, nonché di cornubianiti e calcefiri vari a wollastonite, diopside, granato, vesuviana, epidoto, brucite, ecc.

Per la facies calcareo—dolomitica di scogliera dell'Anisico inferiore possiamo invece ricordare un altro giacimento, da noi pure trovato nello stesso settore meridionale dell'Adamello. E' questo il giacimento di contatto del M. Costone, a cavallo fra la Valbona e la val Stabio, che fu oggetto di una memoria dettagliata da parte di O. Hieke. Si tratta di lenti di calcefiri e cornubianiti immerse in una massa dioritica, che presentano come minerali caratteristici di neoformazione metamorfica: fassaite, granato, xantofillite, epidoto, vesuviana e brucite.

Influenze metamorfiche in complesso analoghe a quelle dell'Anisico inferiore calcareo—marnoso hanno subito anche i sovrastanti sedimenti dell'Anisico superiore, come abbiamo potuto rilevare sia sul M. Frerone nell'Adamello meridionale sia sul Forcel Rosso fra la valle di Fumo e la valle di Adamè.

(e) *Facies metamorfiche nei terreni del Ladinico inferiore (zona a *Protrachyceras reitzi*).*—Nelle stesse località testè menzionate del M. Frerone e del Forcel Rosso si possono osservare in facies altamente metamorfica gli strati di Livinallongo (Buchenstein), rappresentati da marmi saccaroidi, banchi di cornubianiti verdastre a diopside con anfibolo e vesuviana e banchi di cornubianiti rossastre a biotite e granato. A questi si accompagnano anche letti di arenarie metamorfiche macchiettate (*Fleckschiefer*), a biotite, sillimanite, cordierite, tormalina e feldispato, e di conglomerati quarzosi minuti, che hanno assunto facies gneissica e tessitura scistosa.

(f) *Facies metamorfiche nei terreni del Ladinico superiore (zona a *Daonella lommeli*).*—Anche gli strati di La Valle (Wengen) appaiono sul M. Frerone in facies intensamente metamorfica, sotto

forma di arenarie rosso-violacee scure con pronunciata cristallinità e con una diffusa granulazione secondaria di biotite idiomorfa, accompagnata da plagioclasio, tormalina e zoisite.

(g) *Facies metamorfiche nei calcari dolomitici di Esino (Ladinico).*—In genere, le masse calcareo-dolomitiche di Esino hanno subito per effetto del contatto un semplice fenomeno di ricristallizzazione, che le ha trasformate in marmi bianchi saccaroidi. E anche là dove la roccia sedimentaria sia a contatto diretto con quella eruttiva, come avviene in Val Cadino e in val Fredda, l'alone metamorfico a silicati calcio—magnesiaci è per lo più limitato a uno spessore di qualche centimetro o di pochi decimetri al massimo. Non manca tuttavia anche nella dolomia di Esino qualche tipico giacimento particolarmente ricco di nuovi prodotti metamorfici. Uno di questi trovasi a quota 2591 del M. Frerone e fu da noi affidato in particolare studio al compianto allievo nostro G. De Lucchi. In questa località si sviluppano, su un'area relativamente estesa, caratteristici calcefiri disseminati di cristalli idiomorfi di granato, vesuviana e diopside accompagnati da epidoto o thulite.

Limitate ma eleganti aureole metamorfiche policrome si osservano alle salbande di sottili vene aplitiche, che tagliano le zolle di marmo di Esino immerse entro la diorite di M. Cadino in Valfredda (Adamello meridionale). Sono cornubianiti pirosseniche e pirossenico—epidotiche, nelle quali si trovano come minerali accessori variamente distribuiti in zone: orneblenda; apatite, thulite, wollastonite, spinello, xantofillite, olivina e, attorno a questa, anche serpentino e calcedonio.

Il minerale xantofillite, che fu per la prima volta da noi segnalato in Italia fra i prodotti metamorfici di contatto del M. Costone, si ritrova pure nelle lenti di calcefiri e cornubianiti a silicati vari comprese in piena massa tonalitica presso il Rifugio Rosa al lago della Vacca (Adamello meridionale).

(h) *Facies metamorfiche nei terreni del Carnico.*—La dolomia carinata degli strati di S. Cassiano, da noi individuata sulla cresta settentrionale del M. Frerone e sulla sella fra il Farinas del Frerone e la q. 2591, non presenta particolari facies mineralogiche di contatto, al pari della dolomia carinata del Trias inferiore. Invece gli strati di Raibl, che affiorano sul valico di Forcel Rosso, già preso in considerazione nelle pagine precedenti, sono rappresentati da originarie rocce pelitiche e psammitiche evidentemente metamorfiche, con minuta tessitura filladica o nodulare e con diffusa mineralizzazione a biotite e tormalina attorno a isole granulari di plagioclasio e cordierite.

(i) *Facies metamorfiche nella dolomia principale (Norico).*—A Forcel Rosso è messo a nudo per una notevole estensione il contatto diretto fra la tonalite della Cima di Breguzzo e la dolomia principale dell'anticlinale camuna. La zona d'immediata influenza è caratterizzata dalla presenza di una chiazzeria irregolarmente variegata, ove predominano volta a volta le tinte rosee del granato e della thulite, verdognole dell'anfibolo, del pirosseno e dell'epidoto, brune dell'olivina più o meno limonizzata e gialle del serpentino, il quale ultimo deriva da un'evidente azione tardiva idrotermale sull'olivina stessa. Allontanandosi dalla roccia eruttiva, il grosso della formazione dolomitica consiste in un candido marmo saccaroide.

La stessa facies mineralogica di contatto si ritrova nell'Adamello meridionale, laddove la imponente massa dolomitica del Farinas di Stabio e del Farinas del Frerone è intimamente permeata da vene e filoni dioritici. Alla serie di minerali sopra accennati si associò qui anche spinello, calcedonio e tracce di xantofillite e wollastonite.

(j) *Facies metamorfiche nel Retico.*—Gli originari calcari marnosi nerastri, forse in parte magnesiaci, che rappresentano il Retico inferiore sulla destra della val di Fumo fra malga Breguzzo e malga Casinelle, rivelano anch'essi l'azione metamorfica nella grana saccaroide degli straterelli calcarei e nella presenza di sottili letti silicatici con tremolite, olivina, flogopite, ecc. All'estremità settentrionale della lingua di marmi bianchi dolomitici, che si protende entro la tonalite fin sopra malga Breguzzo rappresentando il Retico superiore e forse anche la base del Lias, si trovano calcefiri a diopside e spinello con epidoto e granato come accessori.

Questa rapida rassegna delle principali formazioni metamorfiche di contatto offre una chiara idea della complessità di *effetti selettivi* esercitati dalla massa magmatica sui vari termini della serie stratigrafica direttamente interessati dall'intrusione. La molteplicità delle facies metamorfiche di



contatto si rivela anzitutto come conseguenza della svariata composizione dei materiali originari che hanno subito l'influenza del magma.

D'altra parte, ad arricchire il quadro delle manifestazioni, si contrappone a questi effetti selettivi una serie di *fenomeni di convergenza metamorfica*, per cui terreni molto diversi per età e struttura, ma affini per composizione, offrono attualmente una grande somiglianza di facies mineralogica. Basterà ricordare a questo proposito l'analogia di caratteri che presentano fra loro certi tipi metamorfici entro le formazioni psammitiche e pelitiche del Werfen, del Livinallongo e del Raibliano nella zona di Forcel Rosso, oppure nelle dolomie dell'Anisico, del Ladinico e del Trias superiore tanto a Forcel Rosso quanto nel settore meridionale dell'Adamello.

Molto meno evidente risulta un effetto selettivo in conseguenza della diversa composizione chimica della roccia magmatica. Tuttavia anche a questo riguardo si può notare un differente comportamento dei filoni acidi rispetto a quelli basici, che attraversano le formazioni sedimentarie al margine meridionale del massiccio. Infatti le apliti e le altre iniezioni leucocratiche esercitano una influenza di contatto generalmente assai più vasta ed intensa di quella dovuta ai filoni melanocratici. I più istruttivi esempli a questo riguardo sono offerti dalla parete meridionale del M. Frerone in alta Valfredda.

*Processi metasomatici.*—In tanta ricchezza di manifestazioni metamorfiche, non mancano nel plutone dell'Adamello *processi metasomatici di contatto*, per quanto gli scambi di sostanze non assumano generalmente grande intensità e largo sviluppo. Perlopiù si avverte come causa fondamentale dei fenomeni metamorfici l'azione termica, giacchè la maggior parte delle sostanze necessarie per impartire alle rocce la loro nuova facies mineralogica era già presente nelle formazioni incassanti. Ciò è stato dimostrato in particolare per quanto riguarda l'Anisico da R. Minozzi, con lo studio chimico—petrografico di un interessante giacimento dell'alta val Cadino, nel quale l'apporto di nuove sostanze da parte delle soluzioni magmatiche consiste essenzialmente in una limitata aggiunta di silice e allumina. D'altra parte, anche dove più fitta è la rete di apofisi e filoni variamente differenziati, come per esempio in tutta la regione compresa fra la valle di Stabio e l'alta valle del Caffaro, non si osserva quasi mai un intimo scambio di sostanze adeguato alla vastità e all'intensità dell'effetto metamorfico generale. Ciò riguarda soprattutto i filoni basici, che presentano margini nettissimi e senza alone metasomatico, mentre invece le iniezioni filoniane acide hanno esercitato una più evidente azione metamorfica, che senza dubbio va messa in rapporto con una maggior ricchezza originaria di vapori, di gas e di soluzioni.

Ancor meno penetrabili e quindi poco suscettibili di scambi, si dimostrano gli innumerevoli lembi calcareo—dolomitici dell'Esino immersi entro la massa granitico—granodioritica di Valfredda e Valbona, attorno al M. Cadino, che non hanno risentito vistosi processi di assimilazione e di iniezione magmatica. Essi appaiono come candidi marmi saccaroidi con un'aureola metamorfica di pochi centimetri o al massimo di qualche decimetro di spessore.

In contrapposto a quanto si è detto, non mancano però esempli di chiari processi metasomatici di varia natura. Il caso più interessante finora messo in evidenza dalle nuove ricerche è quello del giacimento a wollastonite e altri minerali di contatto presso Alpe Bazena, descritto da G. Schiavinato. In seguito alle intime reazioni di scambio fra i calcari puri incassanti e il materiale eruttivo, si sono originati qui tipici "skarn", andraditico—hedenbergitici di origine pneumatolitico—metasomatica, nonchè cornubianiti e calcefiri vari a wollastonite, vesuviana, granato, diopside, epidoto, albite, e brucite, che denotano una genesi pneumatolitico—idrotermale svoltasi secondo l'autore in condizioni di temperatura e di pressione piuttosto elevate.

Anche i calcefiri cornubianitici a xantofillite del M. Costone in Valbona e del lago della Vacca, ove questo raro minerale è accompagnato da granato, fassaite, spinello, epidoto e talora da vesuviana, thulite, flogopite e brucite, hanno tipico carattere di sostituzioni metasomatiche, che hanno quasi completamente trasformato lembi di calcari dolomitici compresi in rocce dioritiche.

L'intima penetrazione di diorite nella dolomia principale del Farinas di Stabio e del Frerone

attraverso una fitta rete di apofisi filoniane e di vene, ha prodotto un altro interessante giacimento di contatto, il cui studio di dettaglio fu da noi affidato al dott. Metodi Konstantinov di Sofia come tema per il suo perfezionamento in Scienze geologiche presso l'Università di Padova. In questo caso i processi metasomatici hanno dato luogo in un primo tempo a calcefiri a olivina, granato, fassaite, thulite, epidoto con tracce di xantofilite, spinello e wollastonite, mentre in una fase tardiva a carattere idrotermale si è avuta la sostituzione del peridoto con serpentino, calcedonio, pennina, talco e magnetite.

Analoghi scambi di sostanze abbiamo recentemente constatati al contatto fra tonalite basica e dolomia principale sul valico di Forcel Rosso fra le valli di Fumo e di Adamè.

In qualche caso è avvenuta addirittura una sostituzione radicale, che ha lasciato lenti di granatite nei marmi di Esino dell'alta val Bazenina, oppure noduli e letti irregolari di cornubianiti granatifero—pirosseniche ad epidoto sui fianchi del M. Frerone.

Anche in tutt'altro settore dell'Adamello, cioè nel gruppo del Baitone, vennero già osservate e descritte da W. Salomon e da C. Gottfried lenti e vene di granatite nonché di "skarn", granatiferi a diopside hedenbergitico e biotite, che i suddetti autori interpretarono come prodotti di origine pneumatolitico—metasomatica.

Una diffusa penetrazione di vapori e soluzioni di origine magmatica si può pure invocare per la genesi della scapolite e del dipiro, talvolta accompagnati da un anfibolo tremolitico, nei calcari marnosi dell'Anisico in Valbona e in Valcamonica.

Presso l'immediato contatto con le formazioni marnose, calcaree e dolomitiche del Trias, la roccia eruttiva presenta ordinariamente un alone più chiaro di qualche decimetro fino a qualche metro di spessore, nel quale si rileva un netto impoverimento di componenti femici, una sostituzione quasi totale dell'orneblenda con augite e un arricchimento di titanite, oltretutto la saltuaria presenza di thulite e granato all'estremo limite della massa magmatica. Questo fatto induce ad escludere un vasto e considerevole assorbimento di sostanze estranee da parte del magma. Tuttavia, al margine meridionale dell'Adamello, abbiamo potuto osservare anche esempli innegabili di assimilazione su larga scala. E' questo il caso della massa dioritico—gabbrodioritica del M. Blumone, caratterizzata da una grande instabilità di facies e di grana cristallina, nonché dall'inclusione di lenti cornubianitiche e dalla presenza di frequenti breccie di contatto a fassaite, orneblenda, antigorite, ecc. In seguito a un approfondito studio chimico—petrografico, l'allievo nostro dott. D. Colbertaldo ha potuto dimostrare l'arricchimento di calcio e magnesio e la perdita di potassio subiti da questa massa dioritica, che occupa quindi un posto particolare nell'ampia gamma delle differenziazioni femiche dell'Adamello.

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# THE PROCESS OF NEPHELINIZATION

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## ABSTRACT

The concept of nephelinization was suggested by the writer in lectures 1939–40, and in a preliminary report on the alkaline rocks of Alnö, published in Swedish, 1942. Independently, Gummer and Bun in 1943 used the same term when referring the generation of nepheline in the Haliburton-Bancroft district to the reactions of granitic or syenitic juices on limestone. To this as well as to the word “nephelinization” Chayes raised objections in 1945.

The writer has found the nepheline-syenites of Alnö, previously described as magmatic, largely to be nephelinized migmatites. A smaller part may be either rheomorphic fenites, or hybrid products of the originally intruded carbonatitic magmatic liquid and the substances withdrawn from the wall-rocks during the process of fenitization. The fenitization has progressed as follows :—

- (1) Thermodynamic shattering of the micro-structure of the migmatite ;
- (2) Introduction of  $\text{CO}_2$ , F,  $\text{H}_2\text{O}$  and CaO, and loss of  $\text{SiO}_2$  and  $\text{Na}_2\text{O}$ , resulting in formation of ægirine (ægirine-augite) and hydration of the feldspars ;
- (3) Dehydration accompanied by introduction of  $\text{K}_2\text{O}$  and loss of  $\text{SiO}_2$  (some  $\text{Al}_2\text{O}_3$ ), resulting in formation of soda-orthoclase followed by nepheline ;
- (4) Introduction of  $\text{P}_2\text{O}_5$  and  $\text{TiO}_2$ , high oxidation ratio, and loss of  $\text{Na}_2\text{O}$ , resulting in decomposition of ægirine and formation of melanite and apatite ;
- (5) Liquefaction and removal of the leucocratic minerals, resulting in an enrichment of the femic minerals.

THE map of the alkaline rocks of Alnö Island published in 1895 shows an area of nepheline-syenites surrounded by marginal syenites and a narrow ring of metamorphosed Archæan gneiss-granite. The author, Professor A. G. Högbom, described the nepheline-syenites as magmatic rocks and the syenites as mixed rocks originated from the assimilation of gneiss-granite by an alkaline magma.

My remapping of the Alnö area in the years 1936–42 resulted in a radically changed picture of the occurrence ; the major part of the nepheline-syenites and syenites were found to be migmatites metasomatically altered “in situ.” In the case of the nepheline rocks the concept of “nephelinization” was suggested in a preliminary report published in Swedish in 1942.

Independently, Gummer and Bun in 1943, used the term “nephelinization” when referring the generation of nepheline in the Haliburton-Bancroft district to the reactions of granitic or syenitic “juices” on limestone. To this interpretation as well as to the term “nephelinization” Chayes raised objections in 1945.

In the present case, however, the process of nephelinization is quite different from the one advocated by Gummer and Bun,—the lime participant of the metasomatic process having been the active partner and the siliceous rocks the passive one. The nephelinization at Alnö is the concluding stage of the process of fenitization of the Archæan wall-rocks caused by an intruding carbonatitic magmatic liquid. The most important result of the ionic exchange at the contacts has been a desilication of the Archæan rocks and a silication of the intrusive rock.

The fenitization process began with the thermodynamic shattering of the micro-structure of the migmatite, caused by a rise in temperature and an increase of internal pressure. Its effect is noticeable in the granulation of the quartz grains and in the increase of their optical strain. An intense perthitization of the feldspars due to ex-solution may be referred to the same cause.

The next step involved the introduction of  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , F and CaO and the removal of  $\text{SiO}_2$  as well as some  $\text{Na}_2\text{O}$  ; the migration of the last named being subject to the original sodium content of the



migmatite exceeding a certain limit. The resultant alterations of the migmatite are : the hydration of sillimanite and feldspars, the disappearance of biotite and hornblende and the formation of ægirine or ægirine-augite. The pyroxene forms rims around the diminishing quartz grains and is in turn surrounded by rims of soda-orthoclase. At the point where all the quartz has disappeared the feldspars are generally totally hydrated into montmorillonitic, sericitic and natrolitic products, except the previously mentioned soda-orthoclase, which remains unaffected and even recrystallizes into long narrow Carlsbad-twinned laths. At this zone of maximum hydration the titanium, originally bound to the biotite, occurs as titanite ; the lime having been supplied either by the decomposed anorthite molecule of the plagioclase or by migration from the intrusive.

Likewise, the lime of the pyroxene may derive from either of those two sources, while the soda of the pyroxene may have been supplied by either or both of the decomposed biotite and albite.

When the fenitization continued beyond the point of maximum hydration, dehydration took place and nepheline was formed. Within the kernels of the hydrated feldspars small translucent patches appear which spread outwards towards the grain borders. Already at an early stage of the process shadowy indications of the typical crystal faces of nepheline arose out of the fibrous maze a short distance outside of the translucent central patch. As the homogeneity increased the crystal boundaries moved outwards. The micro-picture differs considerably from that obtained when a magmatically crystallized nepheline is hydrated. In that case no successive sets of crystal boundaries are met with, the outer contour being the only one discernible at the end of the metamorphosis. In the metasomatically generated nepheline, however, the hydration proceeds regularly and conformably to the crystal symmetry from the kernel outwards, whereas the hydration of the magmatically crystallized nepheline generally proceeds irregularly from the margin towards the centre.

The different modes of genesis of the two types of nepheline are also emphasized by their compositions. Generally, the Alnö nepheline is rich in potash-nepheline and crystals have been analyzed which contain up to 40 per cent and more. The average value seems to be about 33 per cent and the lowest about 20 per cent. This applies to both types, but while the magmatically crystallized nephelines are increasingly potassic towards their centres, the metasomatically generated ones are increasingly sodic.

This is a logical consequence of the ionic exchange between the nephelinization-zone of the fenite and the intrusive. The dehydration of the fenite involved not only a loss of water, migrating outwards, but also a further loss of silica in the case of the montmorillonitic and natrolitic hydration products. In case of migmatite components rich in soda a definite loss of soda has also been established. The silica and soda migrated towards the intrusion centre in exchange for immigrating ions, mainly potash and carbonic acid, besides some barium, phosphorus and titanium.

While, in consequence, the "in situ"-formed nepheline gradually became increasingly rich in potash-nepheline up to an upper limit of about 37 per cent, the nepheline crystallizing in the highly potassic magmatic liquid started at a potash-nepheline percentage of about 40 and absorbed more and more soda as the fenitization proceeded until a lower limit of about 20 per cent was reached.

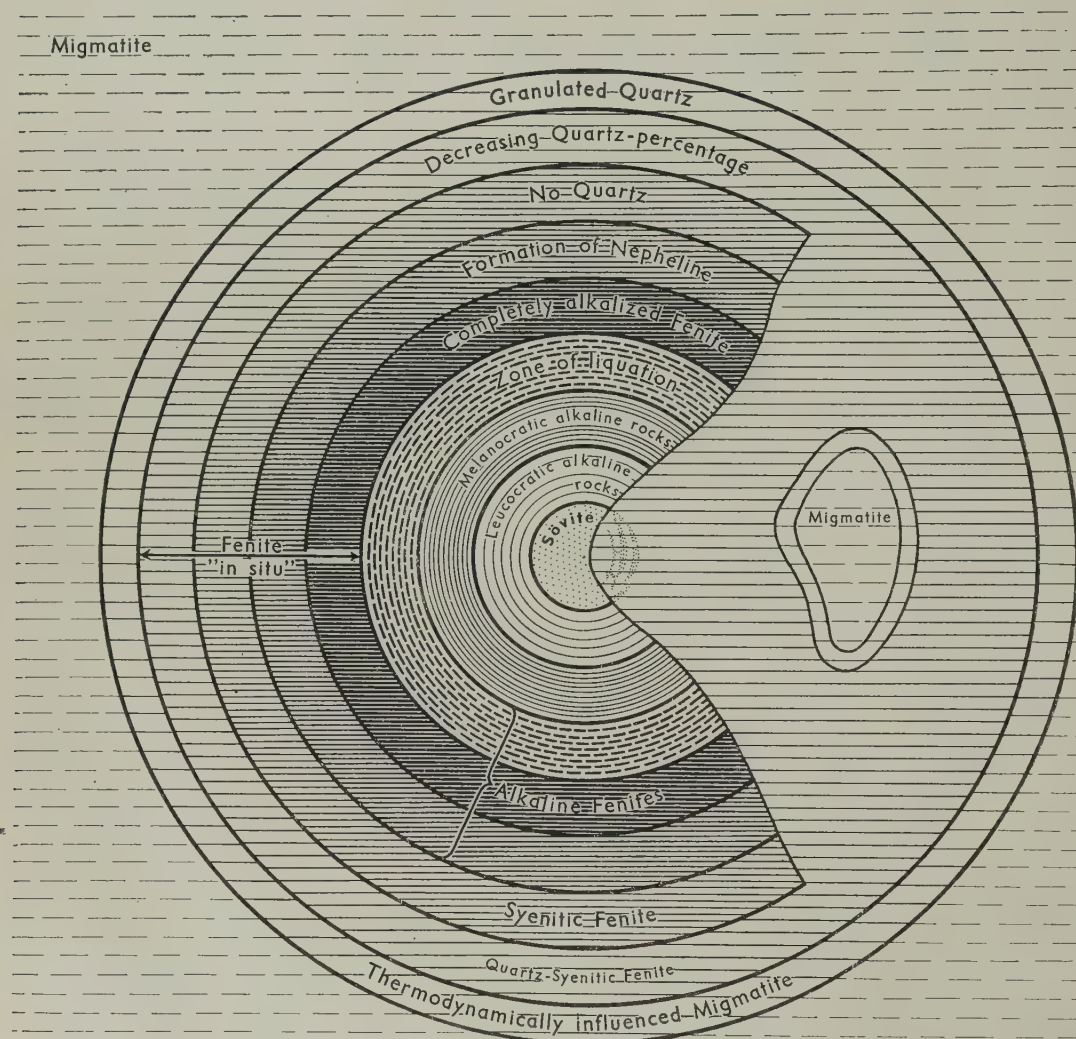
During the last stages of fenitization an increased exchange of soda was brought about by the decomposition of the ægirine molecule of the pyroxene. Chemically, this is illustrated by an accelerated rise of the Niggli "k"-reference value as the fenitization proceeds beyond the zone of maximum hydration. At the same time the oxidation ratio increased conspicuously, certainly due to an increasing concentration of CO<sub>2</sub> towards the inner fenite boundary. Mineralogically, this is expressed by the disappearance of ægirine and titanite, the alteration of the ægirine-augite into diopsidic augite and the crystallization of melanite ; the latter containing up to 17 per cent trivalent titanium oxide.

Close to the innermost fenite boundary a rapid fall in the percentage of felsic mineral components may be observed and a corresponding increase in the mafic ones. With rise of temperature and CO<sub>2</sub>-pressure the nepheline and the soda-orthoclase evidently reached a point where they liquefied, leaving a pyroxenitic or melanitic "rest-fenite." Where the intrusion borders on a very leucocratic fenite (migmatite) the pyroxene has been replaced by wollastonite, sometimes pectolitic.

### PART III: METASOMATIC PROCESSES IN METAMORPHISM

An interesting aspect of the Alnö fenitization is the increase of potash even during nephelinization. This suggests a reversal of the normal mobility of the potassium and sodium ions, which in this case seems neither to be governed by the size of their ionic radii nor to agree with the common metasomatic rule that the sodium precedes the potassium.

To begin with, pressures of thousands of bars are involved and the greater compressibility of potassium may account for the diffusibility of potassium increasing more with pressure than that of sodium, as suggested in another petrological case by J. Bugge. Secondly, the direction of movement may have been governed not by the ionic radius alone but by equilibrium conditions connected with the composition of the primary alkaline intrusion. This latter, as shown by samples drawn from depths approximately calculable by means of the foci of the cone-sheets, was excessively potassic and only very slightly sodic, in striking contrast to the generally predominantly sodic character of alkaline intrusions.



AB KARTOGRAFISKA INSTITUTET

FIG. 1.—A schematic representation of the position of the nephelinization zone within the fenite aureole of Alnö at about the present erosion level.



With the exception of relative changes due to the previously mentioned ex-solution at the inner fenite boundary there is no evidence of the alumina and magnesia having taken any major part in the metasomatic transports leading to nephelinization. A slight addition of both potash and alumina seems to have occurred, however, during the fenitization of feldspar-quartz pegmatites. Generally speaking, it may be taken that the alumina remained nearly "in situ" during the fenitization and the subsequent nephelinization, only changing its partners and positions in the crystal lattices with progressing metamorphism. It may be worth stressing that, in spite of the great amount of potash, the equilibrium conditions seem in no case to have been favourable to the formation of either leucite, or of independent kaliophilite or kalsilite, as these minerals have so far not been found in either the fenites or the main intrusives of Alnö. (In the case of the dike rocks there is some doubt : where the average nepheline contains 47 per cent kaliophilite, two minerals may be present.) No other alkali-silicates but nepheline and soda-orthoclase (occasionally anorthoclase) occur ; the former with up to 37 per cent Kp and the latter with up to 30 per cent Ab. Plagioclases, as well as pure orthoclase and albite, are generally absent. In the case of the nephelinized fenite the crystallization order is : soda-orthoclase  $\rightarrow$  nepheline ; and in the case of the alkaline intrusive rock : nepheline  $\rightarrow$  soda-orthoclase ; indicating desilication and silication, respectively.

Megascopically and tectonically the different fenitization zones may be characterized and recognized as follows, (See Fig. 1) :

- (1) *The thermo-dynamic shock zone* by its slightly opalescent quartz grains,
- (2) *The quartz-syenitic zone* by its undisturbed original strike and dip, by the slightly enhanced colour-contrast between leucocratic and mesocratic migmatite components, and by its low quartz content,
- (3) *The syenitic zone* by its equally undisturbed strike and dip, by the strongly enhanced colour-contrast of the components, by the total absence of quartz and of any fresh original feldspars, and by its content of occasional small soda-orthoclase laths at its inner boundary (the zone of maximum hydration).
- (4) *The zone of nephelinization* by a gradual change of the strike into concentric and the dip into confocal, and by the very strongly enhanced colour-contrasts of the original migmatite components (still indicating the big-scale structure of the migmatite) ; also by the appearance of small hexagonal or square, colourless, grayish or whitish nepheline kernels within the reddish hydrated feldspars (nicely visible on weathered surface), gradually increasing in size and numbers ; and finally by the crystals of lustrous black melanite,
- (5) *The inner zone of fenitization* by its concentric strike and confocal dip, the colour-contrast still remaining but being evidently displaced in comparison with the original structure of the migmatites ; by the gradual liquefaction and withdrawal of the felsic components and by an increased pyroxene, melanite and apatite content,
- (6) *The inner fenite boundary* by its pyroxenitic "rest-fenite" bordering on rheomorphic (liquefied) fenites or hybrid alkaline magmatic rocks, or in the case of fenites originally poor in Fe and Mg by the occurrence of wollastonite.

#### DISCUSSION

See page 100.

# THE GENESIS OF THE ALNÖ ALKALINE ROCKS

By HARRY VON ECKERMANN

Sweden

## ABSTRACT

The limestone masses associated with the alkaline occurrence of Alnö were interpreted by Daly as xenolithic inclusions partially dissolved in nepheline-syenite magma or in some antecedent magma from which the latter was a derivative. The nepheline-syenite surrounding most of the limestones has now been found to be nephelinized fenite while the carbonates (sövitess) occupy the ring-dike and cone-sheet fractures of a volcanic breccia. The correctness of this interpretation is amply verified by numerous drill-holes.

While the ring-dikes surround a subsidence of some 300 feet, the cone-sheets indicate a focus at about 3,200 m. below erosion level at the time of brecciation. Two other systems of cone-sheet fractures with focal depths of 4,000 and 9,000 m. are occupied by calcitic dike-rocks (alvikites) and dolomitic ones (beforsites), respectively. Each system is accompanied by linear radial dikes of alkaline rocks.

It is suggested that the gradual change of dolomitic carbonates into calcitic as well as the formation of alkaline rocks results from metasomatic interchange of substances between the wall-rocks and a high-tensioned dolomitic magmatic liquid, rich in fluorine and potash. From the evidence of mineral syntheses and the samples of rocks delivered by the cone-sheets from definite levels, an approximate PTX-diagram of the Alnö intrusion to a depth of about 6 miles has been constructed.

The probability of older carbonate bodies occurring within the migmatites at such depths seems very remote. In any case "limestone syntexis" at Alnö is no longer "an objective fact."



FIG. 1.—Daly's map of Alnö, redrawn after A. G. Högbom.

G=gneiss. A=metamorphic aureole in gneiss; solid black=limestone; heavy dots=limestone with nepheline-syenite. S=syenite. N=nepheline-syenite.



THE limestone masses associated with the nepheline-syenites of the Alnö Island in the Baltic, were interpreted by Högbom in his description of 1895 as segregations of calcite within a magma rich in lime. To begin with he did not express any definite view on the subject of the origin of the lime and carbon dioxide but later he believed it best to adopt Daly's hypothesis and assume deep-seated limestone syntaxis in order to account for the limestones as well as for the nepheline-syenites, even though limestone does not outcrop for many hundred of miles in any direction around Alnö. He adhered, however, to his previous interpretation of the now observable limestones as being magmatically crystallized concentrations.

Daly himself went one step farther and used Högbom's schematically redrawn map (Fig. 1) as an illustration of partly digested limestone xenoliths within an alkaline magma, adding the following commentary: "Whatever the origin of the limestone masses at Alnö, their partial solution in nepheline

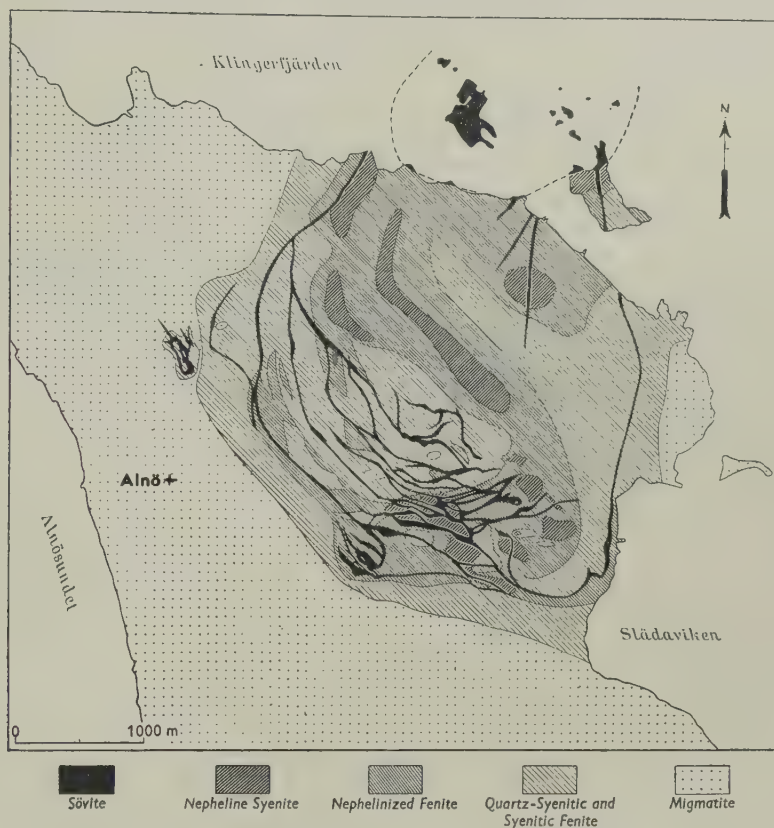


FIG. 2.—Map of the alkaline part of Alnö Island.

syenite magma, or that from which nepheline syenite has been derived, is an objective fact." Since then the geology and petrology of the Alnö area have been completely revised and the new map (Fig. 2) is based on numerous new outcrops in road cuttings, extensive uncovering of the bed-rock and a score of diamond drill holes. Very little remains of the representation of the old map; the new mapping having shown that most of the nepheline-syenite is nephelinized fenite, that the limestone occurrences occupy extensive ring-dike and cone-sheet fractures of decidedly volcanic character and that their tectonic emplacement is very likely that of a diatreme.

Using the nomenclature adopted by Brögger for the Fen alkaline area, the limestones may be termed sövites. The sövite ring-dikes surround a subsidence of some 100 metres while the average 55° dip of the sövite cone-sheets indicates, when projected downwards, a focus at about 1,200 metres

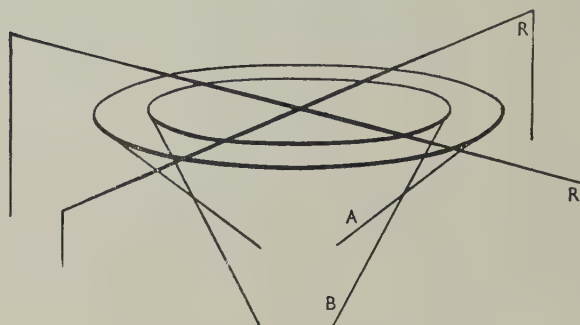


FIG. 3.—A = *alvikites*, B = *beforsites*, R = *radial dikes*.

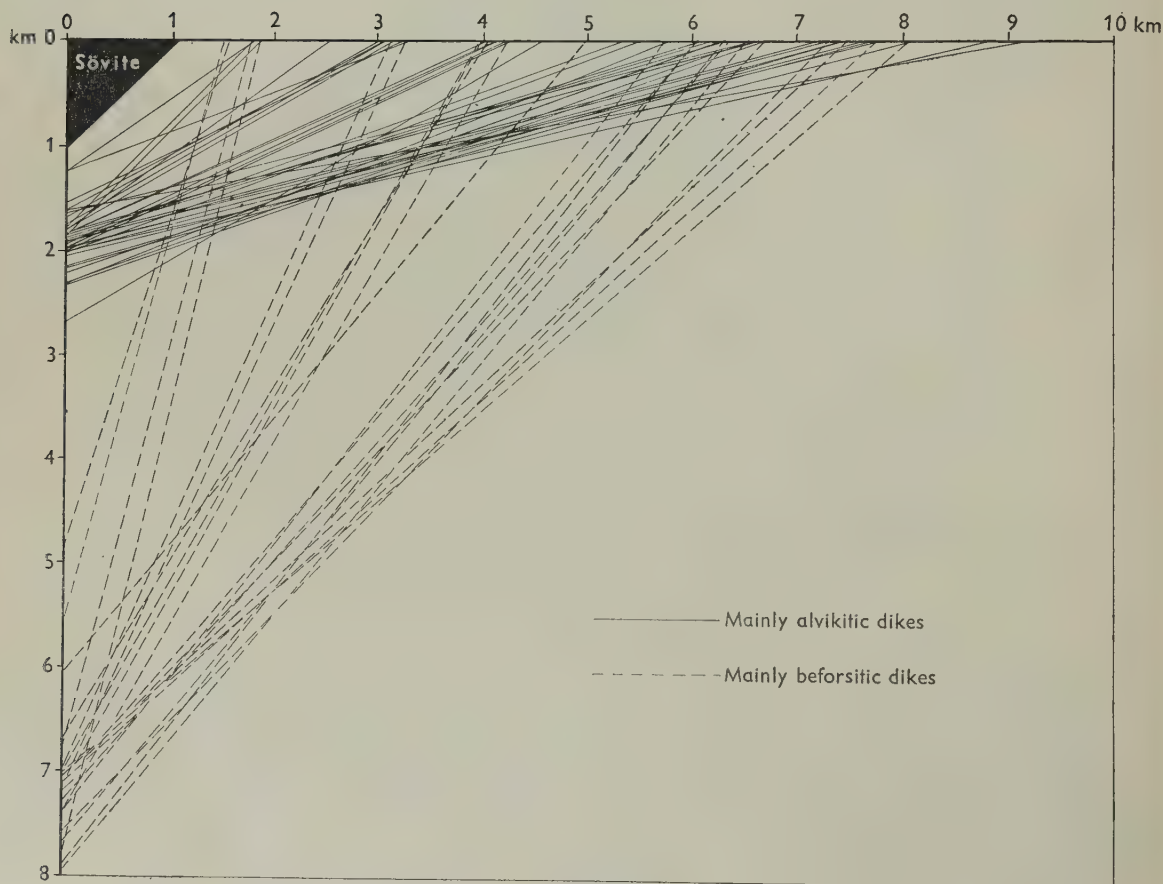


FIG. 4.



below the present erosion level. Assuming a specific gravity of 2.5 and a tensile strength of 500 kg/cm<sup>2</sup> for the overlying rocks, the depth of that focus at the time of the brecciation may be calculated at approximately 3,200 metres. Taking into consideration the coinciding position of the sub-Jotnian and sub-Cambrian peneplanes slightly above the present summit-level of the adjoining hills west of Alnö, the major part of the 2,000 metres of rock removed by erosion must necessarily have been sediments.

Outside the sövite-breccia, and mostly even outside of the alkaline area proper, two other sets of cone-sheet fractures occur with focal depths of originally 4,000 and 9,000 metres, the foci being approximately situated directly beneath the focus of the sövites. The first set is occupied by carbonatitic dikes of calcitic habit and are termed alvikites, while the later and younger set is occupied by dolomitic dikes, called beforsites. Each cone-sheet system is accompanied by linear radial dikes of which the first and older set generally consists of types equivalent to the main alkaline rocks, mostly foyaite-porphyrries, while the later set embraces alnöitic, kimberlitic and melanite-ouachititic dike rocks (Fig. 3). The radial dikes are generally of slightly younger age than their concomitant cone-sheet dikes.

Consequently, we have had three consecutive and almost explosive shatterings of the surrounding older rocks along the ascending conduit of the alkaline intrusion, the first one having occurred about 3,000, the second one about 4,000 and the last one about 9,000 metres below the erosion surface of those days (Fig. 4). By the study at present erosion level of the consolidated liquid forced into the fractures at great speed, the character of the intrusive magma at different depths has been directly disclosed or may be deduced.

At about 10,000 metres the composition seems to have been that of a carbonatitic melt rich in magnesia, lime, titania, phosphoric acid, potash, fluorine and carbon dioxide; containing some iron oxides, alumina and water as well. The carbonate, when crystallized, is dolomitic.

It is suggested that the gradual change from a dolomitic carbonate at 10,000 metres to a calcitic one at 4,000 metres resulted from a metasomatic exchange between the intrusive liquid and the wall rocks. The study of the fenitization of the adjoining Archæan, of the partly rheomorphic and partly hybrid nepheline-porphyrries, as well as of the radial dikes of corresponding composition at the present erosion level, has shown that the metasomatic action produced a desilication of the wall rocks and a silication of the carbonatitic magma.

This silication, which in every instance must have taken place at pressure-temperature conditions below the dissociation point of calcite but probably at or above that of magnesite, was accompanied by a de-dolomitization of the dolomitic carbonate. Orthosilicates of magnesia were formed, ranging from forsterite to monticellite, which settled gravitationally, leading to the formation of kimberlitic rock-types. At the same time carbon dioxide was released and accumulated towards the top of the intrusion, part of it taking an active part in the fenitization process by decomposing the anorthite component of the plagioclase.

At a level roughly coincident with the present erosion surface, the intrusion reached its highest position, at which the increased internal CO<sub>2</sub> pressure, in comparison with which the partial pressures of H<sub>2</sub>O and F were probably of small importance, reached a point where the resistance of the overlying roof was overcome and the diatreme developed.

According to this interpretation of the collected evidence at Alnö the nepheline-syenites surrounding the central sövite are not the differentiates of any primary sub-alkaline or alkaline magma, but solely the products of the silication of a very basic carbonatitic magmatic liquid rich in volatiles, which exchanged part of its lime, carbon dioxide and potash for silica and soda from the surrounding fenitized rocks. Within this hybrid magma a limited crystal differentiation may have taken place, as a result of the gravitational settling of femic minerals, especially pyroxenes and melanite, and rising of soda-orthoclase and nepheline, leading to the ultimate formation of jacupirangites and juvites, respectively.

An approximate idea of the temperatures prevailing at different depths of the alkaline intrusion and within the zones of fenitization may be obtained by studying the mineral parageneses at the

# PART III: METASOMATIC PROCESSES IN METAMORPHISM

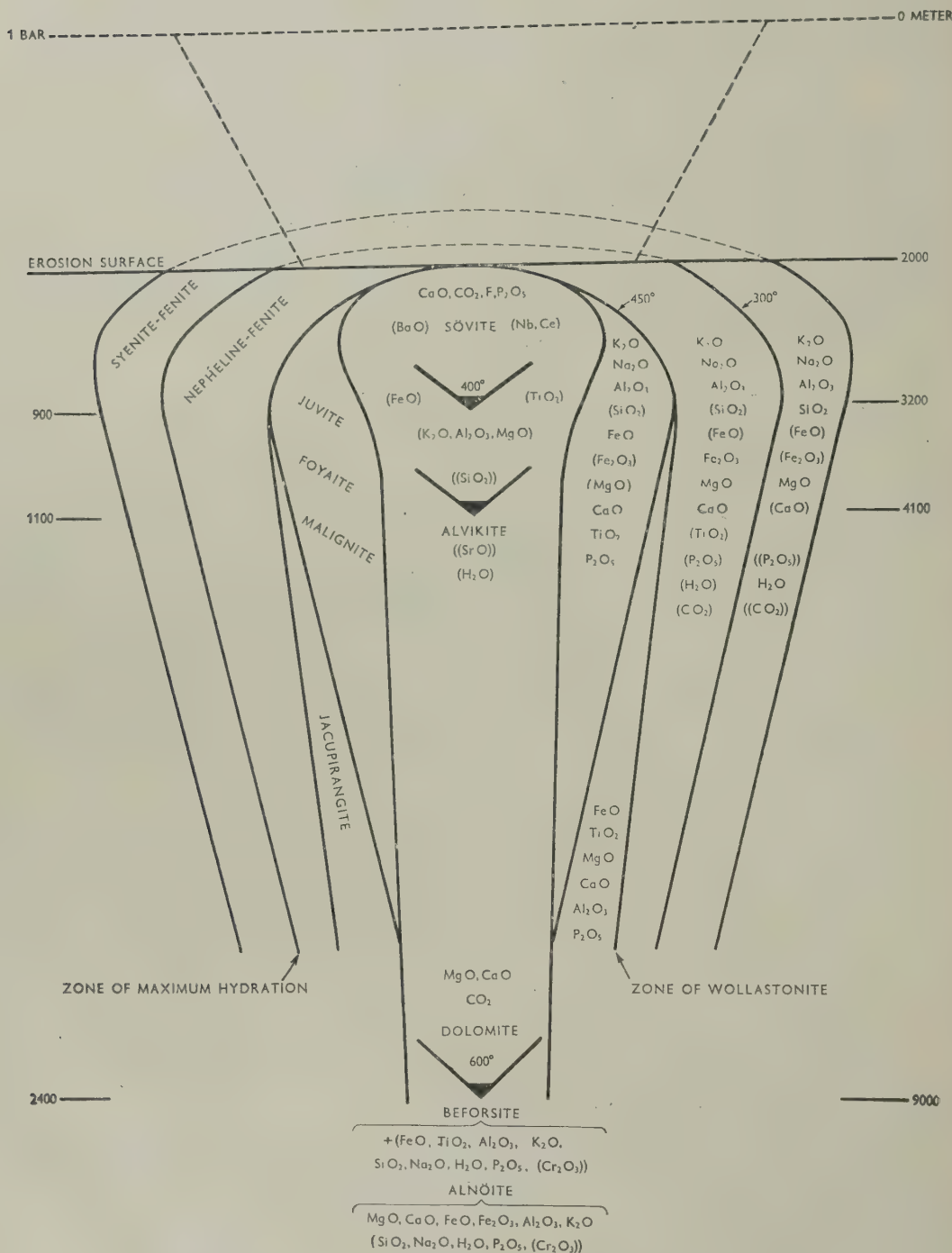


FIG. 5.—PTX-diagram of the Alnö diatreme.



present erosion level and comparing them with the evidence of experimental mineral synthesis. For instance at a zone within the fenite, where all the original feldspars are hydrated, termed the zone of maximum hydration, the experiments of Norton indicate a temperature of about 300°C. At the inner fenite boundary the presence of wollastonite is associated both with the maximum temperature during the process of fenitization and with a very high concentration of volatiles. Judging by the experiments and deductions of Goldschmidt, Kröger, and others, a temperature of about 450°C. is suggested. A drop of 150°C. from the inner fenite boundary to the zone of maximum hydration seems reasonable, taking into account the heat conductivity of the rock and the distance, about 50 to 100 metres.

Further, the synthetic production of nepheline from muscovite has been achieved at about 350°C., which nicely fits in with the position of the zone of nephelinization. The temperature at the 9,000-metres depth level may be deduced either (a) from the fall in temperature during the rise of the magmatic liquid in the conduit up to the 2,000-metres level just discussed, in which connection reference may be made to Graton's paper on volcanic heat, or (b) from the observation that the carbonatitic samples, delivered by the dike rocks from the deepest explosion focus indicate PT-conditions oscillating about both sides of the dissociation point of the magnesite component. Both postulations lead to the inference of a minimum temperature of about 600°C.

By compilation of the chemical elements prevalent at different levels an approximate PTX-diagram of the Alnö intrusion down to a depth of about six miles may now be constructed (Fig. 5). This diagram gives no answer to the question: from whence does the lime derive? but it serves to suggest an origin to be looked for at still greater depths. The presence of lime in the form of limestone at those depths at the time of the alkaline intrusion seems, however, to be very improbable when the following facts are taken into consideration:

- (1) The previously mentioned absence at the present erosion surface of any known limestone deposits or of any amphibolites which might be interpreted as metamorphosed limestones;
- (2) The very advanced granitization of even the best preserved sedimentary relics within the migmatites of this part of Sweden; and
- (3) The deep erosion to which the migmatites, in consequence, must have been subjected; the magnitude being emphasized by the previously mentioned position of the sub-Jotnian and sub-Cambrian peneplanes.

The stage of granitization represented at the present erosion surface is so intense that it seems to preclude even the possibility of a survival of fragments of limestones if such were part of the original sediments. How much less would be the chance of any limestone having continued to exist at the end of the granitization process at depths where the geothermal temperature alone must have been at least 200° and probably 300°C. higher!

Daly's interpretation of the Alnö limestones as xenoliths—in such a case necessarily of post-Archæan age—was severely criticised by Geijer as far back as 1921 and is now completely ruled out by the discovery of the brecciating character of the sövites and the largely remaining brecciated Archæan roof. Moreover, the ratio of Ba to Sr in the sövites, although not yet definitely established by analyses, seems to differ considerably from that characteristic of organic and inorganic Swedish limestones. The continued investigation, now in execution, of the geochemical distribution of the trace elements of the Alnö alkaline rocks may perhaps lead to an acceptable solution of the problem of the origin of the lime.

Backlund's suggestion in 1932 that the answer may be found in the decomposition of the pyroxene seems to have been a step in the right direction, the newly collected evidence supporting the hypothesis that a concentration of CO<sub>2</sub> leads to instability of both the lime-bearing pyroxene and the anorthite component of the feldspar. As implied by Tomkeieff in 1938, the CO<sub>2</sub> is responsible for the formation of magmatic carbonate—but not, as he believed, of calcite; dolomite or even magnesite has in this case now been found to be the primary mineral.

The ultimate problem becomes, consequently, one of explaining the presence and concentration

of the  $\text{CO}_2$  rather than that of the lime. Whatever the final answer to this problem may be, it can in any case be taken as definitely proved that limestone syntexis at Alnö is no longer "an objective fact."

## DISCUSSION

S. J. SHAND said that Dr. von Eckermann had discussed the Alnö complex as if it were a unique occurrence. In the speaker's opinion, Alnö was just an extreme member of a long series of silicate-carbonate intrusions of which two were specially significant. The Sekukuniland (Transvaal) stock was composed of foyaitic and ijolitic rocks almost identical with those of Alnö, with a central mass of crystalline limestone. Since the entire Bushveld complex, upon which the Sekukuniland stock is parasitic, overlay the immensely thick limestone of the Transvaal system, it was surely extravagant to look elsewhere for the source of the great limestone inclusion. About Bancroft, Ontario, the nepheline-bearing rocks were closely associated with what was perhaps the thickest limestone formation in the world. It was easy to trace the normal blue sedimentary Grenville limestone into white, completely crystalline marble, from which veins and tongues of "carbonatite" had been given off and involved with the foyaitic rocks. This region of nepheline-bearing rocks had been studied perhaps more closely and repeatedly than any other, not excepting even Alnö, and no less than *eleven* petrologists had tried to explain the genesis of the nepheline rocks there. The earlier workers all recognized sedimentary limestone as a factor in the problem, but some of the later workers had tried hard—one might almost say desperately—to escape this necessity. They had not succeeded. In one way or another, each of them had been compelled in the end to admit the participation of limestone in the reactions that led to the production of the nepheline-bearing rocks. It was such considerations as these that led the speaker to say that the case for a sedimentary origin of the carbonate rocks at Alnö was not yet closed.

H. VON ECKERMANN, in reply to Professor Shand said he believed the limestone-syntexis to be a fact in several places, but not at Alnö.

E. SAETHER made a brief comparison between the Alnö and the Fen area (Norway). He said that in the Fen area too, the transformation of Archæan gneiss into acmite-syenite (fenite) was a conspicuous feature. The mechanism of this process was the formation of a sanidine, which later, during the cooling of the rock, was converted into microperthite. This sanidine was the only feldspar which was in equilibrium with the alkalic pore liquid, and it was formed both from original potash feldspar and plagioclase (the former absorbing  $\text{Na}_2\text{O}$ , the latter  $\text{K}_2\text{O}$ , from the liquid). The quartz was dissolved and replaced by crystals of the same sanidine. At Fen the original country rock was a granitic gneiss, which had absorbed roughly equal quantities of  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$  during the fenitization, while at Alnö the country rock was a plagioclase-rich migmatite, which had selectively absorbed  $\text{K}_2\text{O}$  and expelled  $\text{Na}_2\text{O}$  to the liquid.

The lack of explosive breccia and cone-sheets in the Fen area represented a difference from the Alnö area. The Fen magma had had no explosive activity; on the other hand, hydrothermal carbonate deposition took place during a very long time under successively decreasing temperature, and a series of rocks were formed in this way. At Alnö this process had been disrupted by the explosive event, which gave the volatiles exit to the atmosphere.

H. VON ECKERMANN in reply to Dr. Saether said that Dr. Saether's description of the fenitization at Fen did not show any real difference from that of Alnö. Where, for instance, potassic rocks poor in soda had fenitized, there was, of course no withdrawal of soda, but there may have been an addition. The same type of soda-orthoclases of sanidine habit was formed at Alnö as at Fen.

A. HOLMES said that in presenting this most welcome summary of his long-awaited study of the Alnö Complex, Professor von Eckermann had convincingly demonstrated the transformation into nepheline-syenite of rocks that were originally of granitic composition. Expressed in the simplest terms this meant that the original quartz was now represented by nepheline with or without a certain amount of alkali-feldspar. Alkalies and alumina had been added, and this could have occurred either with or without the driving out of a corresponding amount of silica. If silica had been driven out, it might now be represented by quartz veins in the rocks surrounding the complex. If silica had not been driven out there must inevitably have been a considerable increase in volume during the nephelinization. He asked Professor von Eckermann if he had found field evidence to indicate which of these two alternatives was the correct one.

H. VON ECKERMANN, in reply to Professor Holmes said that he had to confirm the presence of an increase in volume.

B. C. KING said that much of the difficulty in explaining the association of carbonate rocks with undersaturated suites had been occasioned by the attempt to describe all occurrences in terms of a single petrogenetic process. This the limestone-syntexis hypothesis of Daly had done, whereas in fact it appeared to be applicable only to the development of subordinate masses of undersaturated rocks in relation to larger saturated bodies.

The widely distributed undersaturated soda suite of East Africa could not be explained by Daly's hypothesis. Typically the occurrences consisted of ijolites with a central carbonatite core, while developments of apatite rock were often also present. A direct relationship with volcanic activity was frequently demonstrable. The evidence seemed to be incontestable that carbonatite had existed as a phase of a magma that was rich both in soda and lime, as well as being in a highly carbonated condition, and which developed in relation to a characteristic tectonic environment, but quite independently of the lithology of the invaded rocks.



## VON ECKERMANN : ALKALINE ROCKS OF ALNÖ

W. CAMPBELL SMITH said that in the Chilwa Series of Southern Nyasaland Dr. Dixey had observed that limestones in the rocks surrounding the carbonatite filled vents were completely insignificant in bulk and that they differed in composition from carbonatites. It was difficult to account for the carbonatites of the Chilwa Series as derivatives of earlier sedimentary limestones. Many of the rocks of the Chilwa Series showed resemblances with the rocks of the Alnö district.

A. M. MACGREGOR drew attention to the alkaline ring complexes in Southern Rhodesia, not far south-west of the Chilwa centres, where the limestone and dolomite cores appeared to have the nature of cauldron subsidences, having dropped from the formerly overlying Umkondo formation. (See discussion on carbonatite in the African Section, in Part XIV.)

# METASOMATISM AND METAMORPHISM IN THE PYRITE DEPOSITS OF THE URALS

By A. N. ZAVARITSKY

U.S.S.R.

## ABSTRACT

The pyrite deposits of the Urals, as well as those of other countries, are considered among the most typical metasomatic formations deposited amidst schistose rocks. Investigations made in the Urals have shown that these ore bodies have been formed by metasomatism before the general dynamic metamorphism which altered the country rocks and partially transformed them into schists. The ore bodies themselves were considerably changed both in structure and mineralogical composition. A re-arrangement of the components and the replacement of certain minerals by others took place under new conditions of metamorphism. Thus from the indications of the metasomatic replacement it is not always possible to conclude which of the ore minerals are primary and which are due to metamorphism.

In the slightly metamorphosed deposits colloform textures occur not infrequently. Primary marcasite and wurtzite are found in the least altered ore bodies. These peculiarities disappear in the metamorphosed deposits. The characteristic lens-shaped form of the ore bodies, concordantly enveloped by the schists, is due to the dynamic action of metamorphism.

The differences between the various Uralian pyrite deposits are mostly the result, not of primary ore deposition, but of the different conditions of metamorphism.

**P**YRITIC replacement deposits, which usually occur within the zones of volcanic rocks altered into greenstones and green schists, are considered to be amongst the most typical metasomatic formations. The existence of such pyrite deposits in the Urals was established about 40 years ago and they have been studied continually for over three decades. The investigations of the more southern deposits carried out in the last decade have, however, essentially changed our views as to the genesis of the Uralian pyrite ore bodies. Attention has been given to the rôle of later metamorphism and to the accompanying metasomatic processes. Many features which were formerly believed to be characteristic of the metasomatism of schists that already existed at the beginning of the process of primary ore deposition should now be re-examined.

The new data recorded in the Urals throw fresh light on the origin of pyritic deposits in general, for some of the recorded facts have also been observed in other deposits of the world. The new views can be successfully verified in the Urals because of the especially favourable geological conditions of the pyritic deposits occurring in this area.

The Ural pyritic deposits, except for a few occurrences in the axial zone of the Urals and their western slopes, represent a single group of deposits occurring under similar geological conditions within the zone of Silurian or Devonian volcanics.

As a result of investigations carried out recently in the middle part of the Urals, pyritic deposits are found among the volcanics of Ludlow and Downton ages. In the middle Urals, Upper Silurian conglomerates contain rare pebbles of sericite and quartz rocks highly impregnated with pyrite. These resemble somewhat the country rocks of pyritic ore bodies and were considered a direct evidence that the age of ore deposition was more ancient than that of the beds where these pebbles were found.

The major epoch of folding as well as of large granite intrusions and the metamorphism of more ancient rocks is known to belong in the Urals to the Variscan. The volcanic rocks enclosing pyrite deposits were affected by regional metamorphism, the intensity of the latter varying both along and across their extension. The rocks most intensively metamorphosed are found in the Middle Urals where a belt of volcanic rocks (in which some sedimentary layers are embedded) underwent the most intensive dislocation. The volcanic rocks were changed into porphyroids and green schists and mostly



lost their original texture. In the northern and southern parts of the Urals the rocks are not so intensely crumpled. The changes are therefore less pronounced, and porphyritic, ophitic or tuffaceous textures peculiar to volcanic rocks are well preserved, although their mineralogical composition has been entirely changed and now corresponds to the greenstone facies of metamorphic rocks. In the southern part of the Urals, the Tanalyck-Baimack region, less metamorphosed rocks enclose a narrow belt of more strongly metamorphosed schistose rocks, both of which contain ore bodies. Further south, in the most southern part of the Urals, ore bodies of the Bliava deposits are found within a typical spilitic series consisting of pillow lavas, dikes and sills of keratophyres, and radiolarites interbedded with the volcanic rocks.

Due to the varying intensity of metamorphism, these ore bodies, if actually formed before the epoch of diastrophism and metamorphic changes, are extremely favourable for the study of metamorphic action on pyrite deposits. They enable us to trace different degrees of alteration and to correlate them with those of the country rocks.

Formerly, when few pyritic deposits were known in the Urals and had been studied only in the Middle Urals, they were considered *a priori* to be younger than the regional metamorphism of the enclosing rocks, and the distinction between various deposits was explained as being a result of the different conditions under which the ores were deposited. The time of the formation of pyritic deposits was assumed to correspond to the major epoch of granite intrusions in the Urals.

The pyritic deposits known and described in the Middle Urals occur in green schists, as for example the well known Kyshtim deposits. The deposits discovered in the southernmost part of the Urals differ somewhat from the Middle Urals deposits, and that made us re-examine all the other known deposits. It has been found that the peculiarities of the deposits vary in accordance with the intensity of the regional metamorphism of the enclosing series of volcanic rocks. Clear traces of metamorphism were found in the ore bodies of the Middle Urals. Accordingly, many students interested in the Ural pyritic deposits have now come to the conclusion that, being of the same type, these deposits differ in intensity of metamorphism and that many of the characteristic features considered formerly to be of a primary nature are but the result of different degrees of metamorphism.

If pyritic deposits have been affected by metamorphism together with the rocks enclosing them, such metamorphic processes may have also affected the country rocks which enclosed ore bodies and had undergone changes during the primary deposition of ore by hydrothermal solutions. Where subsequent dynamic metamorphism is supposed to have taken place, the country rocks of ore deposits are usually represented by chlorite- and sericite-schists. Schistosity is not so distinct in less metamorphosed deposits, where the country rocks are not infrequently represented by non-schistose quartz-sericitic rocks. Besides sericitization, chloritization and quartzitization, hydrothermal solutions may have brought about other forms of decomposition, i.e. kaolinization and silicification ; however, such changes were concealed by subsequent metamorphism.

In most cases, however, the mineral composition is not supposed to change greatly under the effect of dynamic metamorphism affecting the country rocks previously altered by hydrothermal solutions. Under these new conditions sericite and chlorite remain stable and only the texture of a rock has been subjected to changes. In this connection, it is interesting to note that coarse sericitic schists recorded in the Degtiarka deposit were considered by L. Duparc 35 years ago to be similar to the metamorphic schists of the Central zone of the Urals. In one of the Middle Ural deposits, "Riabinin Prospect," metacrysts of chloritoid were, however, found in sericite-schists enclosing a pyrite body. That may be considered as an indication of the operation of stress during the formation of the schists.

The rocks altered by hydrothermal solutions were probably less resistant when affected by regional metamorphism. After metamorphism they became more schistose, which resulted in the ore lenses being, after metamorphism, confined to the more schistose zones of the belt of metamorphic rocks. As the hydrothermal alteration is not always accompanied by sulphide mineralization, the more

### PART III : METASOMATIC PROCESSES IN METAMORPHISM

schistose and metamorphosed zones do not necessarily include ore bodies. Although proved by actual investigations, this fact can no longer be considered as an indication of later ore formation in more schistose rocks ; neither does it prove that the more schistose zones provided passage-ways for the ore-bearing solutions.

The process of primary replacement by ore seems to have affected different kinds of rocks, such as volcanic rocks—rather frequently volcanic tuffs and breccias—and occasionally even sedimentary rocks as well. Some ore bodies recorded in the Levykha, San-Donato, Degtiarka and Kaban deposits are crossed by dikes of igneous rocks (porphyrites) which have been more or less affected by dynamic metamorphism.

Close dependence is known to exist between the form of pyrite deposits and the degree of schistosity of the rocks in which they happen to occur. At present this dependence in the Ural deposits is accounted for by the dynamic action of metamorphism.

It was long ago established that under the influence of regional metamorphism the shape of ore bodies and especially of pyrite deposits has been changed as a result of the different competencies of ore and enclosing rocks.

The lenticular form is characteristic of the more competent portions of any rock series affected by metamorphism. It is also characteristic of pyrite bodies enclosed in metamorphosed schistose rocks. Occurring conformably, these lenses seem, in some cases, to disjoin the planes of schistosity bent around them. Such shapes of ore bodies were formerly considered as evidence that sulphide matter (" magma ") had been injected under pressure. If the deposits undergo metamorphism together with the surrounding rocks, this peculiarity may testify to a different competency of ores and rocks and can be explained by the schistose rocks having been bent around more resistant ore masses under outside pressure. In some cases, the boundary of the ore body runs at an angle to the general direction of schistosity, but usually the latter changes its direction at the contact and runs parallel to the wall of the ore. Ore bodies enclosed in non-schistose and less altered rocks are of more irregular form and fairly often follow the contact of sills or dikes. In this connection it is interesting to point out the difference existing between the peculiar lens-shaped form of ore bodies recorded in the rocks of the schistose zone in the western part of the Tanalyk-Baimack region and the more irregular form of the deposits in the eastern zone of the same region.

Other evident deformations of pyrite ore bodies in the Urals are also found in certain deposits. The tabular body of the Degtiarka deposit is bent and crushed and shows slickensides on the displacement surfaces. Such deformations were observed in some other large bodies of pyrite deposits.

When comparing the metamorphism of ores and enclosing rocks, it should be borne in mind that the silicates must be far the more stable minerals in general. It may therefore be assumed that if sulphide ore bodies and the enclosing rocks were simultaneously affected by the same alteration, changes would be far greater in ore bodies. The material composing ore is more liable to migration and recrystallization. Under general metamorphism new formations of ore minerals and their aggregates are believed to originate even more readily than those of the silicates of the enclosing rocks.

It has been established that ores enclosed in volcanic rocks, slightly metamorphosed if at all (the Southern Urals), differ in mineral composition and texture from the ore bodies found in greenstones and green schists produced by the metamorphism of the same volcanic rocks.

In the Bliava and the Yaman Kassy deposits, in the Southern Urals, the ores not affected by metamorphism carry together with pyrite, marcasite and occasionally an earthy variety of  $\text{FeS}_2$  identified with melnikovite. Besides sphalerite, such non-metamorphosed ores carry wurtzite as well.

Colloform textures are very abundant in unmetamorphosed or slightly metamorphosed ore bodies. It is in association with such textures that marcasite and wurtzite are found, e.g. in botryoidal nodules with radial structures. Melnikovite can be found in the middle part of the nodules together with marcasite, or in thin concentric zones. The iron disulphides, as marcasite and melnikovite, are obviously replaced by pyrite, and wurtzite by sphalerite. Traces of colloform texture sometimes



remain visible but usually the ore has been changed into a granular aggregate without any regular arrangement of individuals.

In the Sibai deposit colloform structures are very common, while marcasite and wurtzite are completely absent. Radial forms of pyrite are, however, not an infrequent occurrence, being probably pseudomorphs after marcasite.

When chalcopyrite participates in the formation of colloform structures, it usually alternates with pyrite in the form of thin zones or fills up the fissures crossing the nodules. Sphalerite is to be found in the same way. Minute inclusions of chalcopyrite are also not infrequently distributed zonally in sphalerite and wurtzite nodules.

Recrystallization and transformation of marcasite and melnikovite into pyrite, and of wurtzite into sphalerite, occur mostly outside, but occasionally inside, the nodules of colloform texture.

At present all the investigators of the pyrite deposits of the Urals believe that the marcasite, melnikovite and wurtzite of the Bliava and Yaman Kassy deposits are earlier minerals which underwent recrystallization and transformation into pyrite and sphalerite. In some ores showing colloform textures there occurs quartz in spherical forms which resemble the colloform textures of opal and the spherulites of chalcedony. Primary fine-grained and occasionally drusy structures are to be found in the ores as well, but although present, they are by no means characteristic.

The remains of colloform textures similar to those characteristic of the South Ural deposits have been recently found in the deposits of the Middle Urals, but they are poorly preserved and rather rare. Thus the presence of colloform textures may be considered as traces of the original features which the deposits had before they were affected by metamorphism.

In the ores of the Middle Urals occurring among metamorphic schistose rocks there are common textures well known in most pyrite deposits of other areas.

Pyrite appears as a mineral formed before any others. When predominant it displays traces of mechanical deformation. Its grains are crushed and occasionally transformed into eyes. The fragments of grains are sometimes displaced. As to chalcopyrite and sphalerite they rarely display such signs of deformation. They are completely recrystallized and redeposited almost simultaneously, either filling up the fissures of crushed pyrite or metasomatically replacing it.

In some of the most intensively metamorphosed deposits of the Urals, however, pyrite is also recrystallized, cataclastic structures are absent and the pyritic ore has a granoblastic texture. The individuals of pyrite elongated in the direction of schistosity form a massive aggregate with a texture strongly resembling that of such metamorphic rocks as gneisses or quartzites. Such are the ores at the hanging wall of the Degtiarka deposit, enclosed in porphyroids and schists.

It is well known that the same minerals, as for example quartz, may occur in metamorphic rocks both as a relic mineral, left from the original composition of the rock, and as a mineral formed during the process of metamorphism. While in relic minerals one may observe traces of deformation such as crumbling, undulatory extinction, etc., secondary quartz grains, formed during metamorphism, commonly display none of them whatsoever. The same features may also be observed in the pyrite of pyritic deposits. While some of its grains are broken and crushed residues of primary grains, others have originated during metamorphism.

In some metamorphic rocks the more stable minerals, such as quartz, remained unaltered while others (chlorite and sericite) grew as new minerals during metamorphism. Such is also the case with the ores where, together with residual pyrite, other minerals have been completely recrystallized and redeposited during dynamic metamorphism. As with almost any metamorphic process, dynamic metamorphism was accompanied by metasomatism: crushed grains of pyrite were replaced by chalcopyrite; the inclusions of pyrite and other sulphides developed in silicate country rock replaced the silicates of the rock; thin veinlets were formed, etc.

Taking into consideration the age of the pyrite replaced by chalcopyrite and partly by sphalerite, some students of the Uralian deposits thought that chalcopyrite and sphalerite were deposited during

a second stage of mineralization. At present it is believed that they were redeposited at the time of dynamic metamorphism. Being more stable, pyrite was affected only by mechanical deformations, while the other minerals were almost completely recrystallized and redeposited.

The relations of sulphides in the pyritic deposits of the Middle Urals may be compared with the sequence of the crystalloblastic series of minerals in metamorphic rocks, but not with the sequence of minerals primarily precipitated from solution.

The textural similarity to metamorphic rocks is markedly displayed in ores relatively rich in chalcopyrite and sphalerite which are readily subject to recrystallization. Such ores are often characterized by a banded structure, layers richer in chalcopyrite alternating with those richer in sphalerite. On the etched polished surface of the ore separate layers sometimes display a directive gneissose texture. Some grains of sphalerite and chalcopyrite show thin polysynthetic twinning, due probably to pressure. In such gneissose ores several large grains of pyrite stand out in the manner of "eyes" of quartz and feldspar in eyed gneiss or porphyroid. In some cases grains of chalcopyrite, larger than those of the surrounding mass, develop around crystals of pyrite. They form haloes or tails in the pressure shadows quite similar to those formed by chlorite, sericite and other metamorphic minerals around the eyes of quartz in schistose rocks. This similarity between the ore textures and those of silicate schistose rocks proves that in ores textural relations between different minerals also depend on dynamic metamorphism.

Under the influence of stress, affecting ore deposits, the softer and incompetent enclosing rocks previously altered by ore-bearing solutions became schistose, while in the more stable pyritic bodies there appear transverse fractures occupied by veins of sulphides which were more mobile under metamorphism; namely chalcopyrite, sphalerite, galenite and occasionally tennantite, together with quartz and barite as gangue minerals. These veinlets, some centimetres thick, thinning out in all directions, seem to be analogous to the well known metamorphic veinlets found crossing many schistose rocks. As a rule they cross the schistosity. Their mineral composition corresponds to that of the enclosing rocks. Albite, epidote and quartz are characteristic of green schists; hæmatite and quartz are characteristic of ferruginous jasperoids; amphibole and plagioclase occur mostly in hornblende-schists, etc. The mineral composition of the above-mentioned veinlets crossing pyritic ore bodies similarly corresponds to the composition of these ore bodies. On the contrary in some cases when ores usually rich in chalcopyrite, pyrite and sphalerite are less competent than the comparatively slightly altered country rocks, the ores are characterized by a banded texture and short, thin cross fissures, usually filled up with chalcopyrite, penetrate from the ore bodies into the country rock. Such phenomena are of frequent occurrence in ore deposits near the San-Donato station not far from Nijny Taghyl.

The growth of pyritic crystals in the schists simultaneously with the formation of schistosity long ago attracted the attention of De Magnée. He pointed out that some of the pyrite crystals in the country rocks of pyritic deposits underwent some rotation so that the tails of sericite or chlorite scales originating during metamorphism became sigmoidal. The Ural deposits often display such relations.

In his investigations of the pyrite crystals from Uralian ore deposits S. N. Ivanov used the method of etching by electric current, by means of which an important feature of the structure of pyrite grains from replacement deposits is revealed. When etched they show numerous tiny zones of growth such as characterize the pyrite crystals from less metamorphosed deposits. But this zoning in most cases disappears due to later recrystallization. In the central parts of pyrite cubes from country rock impregnations or of pyrite grains from more or less highly metamorphosed ore bodies, only cores having the outlines of pyritohedrons with distinct zoning are found.

The pyritohedrons of the cores are probably crystals formed under different conditions than the cubes representing the last stage of crystal formation. It seems probable that these cubic crystals grew under new metamorphic conditions during which the primary pyritohedrons turned into cubes.

It should be noted that in those Uralian pyrite deposits which, according to their geological



position, must be considered as highly metamorphosed, pyrite crystals are found only as cubes. Pyritohedrons appear only in less metamorphosed ore bodies\*.

That some of the crystals of pyrite included in the country rocks were undoubtedly growing under metamorphism, suggests that both the secondary impregnation of pyrite and the secondary veinlets or other accumulations of this mineral may have commonly originated during metamorphism. The intensity of the pyrite impregnation caused by metamorphism is not invariably the same, but differs according to the prevailing conditions of the crystal growth. Similarly to the preferred development of certain metamorphic minerals in the pressure shadows around metacrysts, favourable conditions for the formation of metamorphic minerals and their aggregates may occur on a far larger scale at the ends of ore bodies. The appearance of distinctive tails of abundant pyrite impregnation at the ends of the ore bodies along the strike of the enclosing schists can thus be explained.

It is difficult to appreciate the extent of the ore-material migration, but it is evident that redeposition and metasomatic replacement have taken place under metamorphism. Therefore the occurrence of metasomatic replacement or even the formation of separate small accumulations of ore minerals in such a way by no means proves that these processes occurred only simultaneously with the primary deposition of all the ore. They may have taken place during metamorphism.

The evidence showing that the ore-material was deposited in country rocks already affected by metamorphism is not convincing in this case. Thus the presence of thin pyritic veinlets crossing the country rocks was believed to favour the epigenetic deposition of all the ore accumulation. But such veinlets may have appeared later, during metamorphism, at the expense of the material of the ore body. They may have crossed schistose country rocks but at the same time the schistosity of the rocks may have originated after the deposition of the main ore which was thus subjected to metamorphism together with the surrounding rocks. This is to a certain extent analogous to the above-mentioned metamorphic veinlets in metamorphic schists. Their formation appears to occur simultaneously with the process of metamorphism. Even small satellitic ore bodies may have been formed in the same manner.

During metamorphism, migration and redeposition of matter could have brought about a new distribution of metals in the ore deposits, such as an enrichment in Cu and Zn within the ore body. Under regional metamorphism different conditions of ore deposition in various parts of the ore bodies are probably due mainly to a difference in pressure, itself probably dependent on the form of the ore bodies. Thus the form of an ore body is likely to affect the distribution of the redeposited minerals. There is a definite relation between the proportions of Cu and Zn and the outline of the ore bodies. For example it has been established in the Degtiarka deposit that the relative increase in sphalerite and chalcopyrite occurs both vertically and horizontally in the marginal parts of the deposit. Moreover, the amount of these minerals increases somewhat near the foot-wall, where the ore is characterized by a banded texture and replacement of pyrite by sphalerite can be observed. This may account for the peculiar enrichment of the thinner portions of ore lenses which is usually observed in pyritic deposits.

Since in the Urals, as well as in other regions, the peculiarities of the mineralogical composition of the ore were considered only as evidence of different physical conditions of the ore deposition, while the possible changes caused by metamorphism were not taken into consideration, little attention was paid to those facts which from the new standpoint throw light on the paragenesis of minerals.

The mineral composition of pyritic deposits is known to be usually very uniform. Comparatively few minerals are essential components of the ore. The above-mentioned marcasite and wurtzite found in non-altered deposits of the South Urals, though very characteristic, are but very rare minerals. Pyrite, occasionally pyrrhotite, relatively small amounts of chalcopyrite and sphalerite are more or less constant components. Such minerals as tennantite and tetrahedrite, arsenopyrite, magnetite,

\* The pyritohedrons are of much more general occurrence in Caucasian deposits which have not been subjected to such a degree of metamorphism as the deposits of the Urals. The Chiraghidzor, one of the Caucasian deposits, is of interest because of an almost complete absence of cubes of pyrite.

primary bornite, enargite, famatinite, cubanite, native gold and tellurides of gold are rare or occasional minerals in the Uralian deposits.

The mineralogical composition being so uniform, it is almost impossible to notice any difference between the paragenesis of the minerals of metamorphosed and non-metamorphosed deposits (except the above-mentioned marcasite and wurtzite). Up to the present time tennantite has been mainly found in the metamorphosed pyritic deposits of the Urals. On the contrary, enargite was reported, if at all, from slightly metamorphosed deposits. Of interest is the behaviour of native gold whose particles are extremely thin in non-metamorphic deposits but become larger in metamorphosed ore bodies.

We have already mentioned the dikes crossing ore bodies. Metamorphic changes at their contacts are likely to be present but they have not yet been sufficiently studied. Some interesting facts should, however, be pointed out. In the pyrite deposits near the San-Donato station, north of the town of Taghyl, there are dikes of andesitic porphyry (porphyrite) crossing the ore body. At the contacts the pyritic ore is considerably enriched in magnetite, while farther away from the contacts this mineral is absent. This deposit was subjected to a relatively moderate regional metamorphism, judging from the rarely preserved relics of the primary colloform structure. According to some investigators, with whom the author agrees, pyritic ore at the contacts with dikes appears first to have been changed into pyrrhotite and then during later dynamic metamorphism turned into pyrite and magnetite, an association which is more stable than pyrrhotite.

The more northern Kaban deposit consists of a few ore bodies. Some of them are enclosed in schists, others in porphyrites (meta-andesites). Both sets are dissected by dikes of basic porphyritic rocks. Noticeable traces of metamorphism have been discovered in the ore of the deposits occurring among schists. Of interest are characteristic intergrowths of chalcopyrite and bornite in the form of reaction rims at the boundaries of the grains of these minerals. They resemble the artificial intergrowths between these minerals obtained by Schwartz.

The ore bodies enclosed in the better preserved volcanic rocks are less metamorphosed, the ore carrying the relics of colloform textures.

The altered country rocks of the Kaban deposit are very peculiar. They are often represented by quartz-sericite rocks rich in quartz and quartz-sericitic rocks with andalusite, corundum and zunyite.

The mode of formation of the Uralian pyrite deposits has so far not been ascertained in all its details, but our knowledge of their metamorphism enables us to systematize the variety of the deposits discovered during the last few years. This variety has been caused not so much by differences in the conditions of the primary metasomatic formation of sulphide deposits as by variations in metamorphic intensity and in metasomatic processes during metamorphism.

#### REFERENCES

See page 117.

#### DISCUSSION

T. VOGT said he considered Professor Zavaritsky's paper to be a most welcome and valuable contribution to the question of formation of the pyrite deposits of the Uralian Mountains, and in general. In a paper contributed to the Congress, he had entered upon one point as to the similar pyrite deposits of Norway. Here the longer axes of the epigenetic pyrite deposits (they also had some syngenetic) were always conformable to the structure of flowage in the surrounding rocks, i.e. the mechanical stretching and the crystal flowage has occurred during the metamorphism. *A priori*, the pyrite might sometimes have been formed before the metamorphism, but he thought it was more probable and in better accordance with the present facts to consider that the deposits had largely been formed during the metamorphic and tectonic processes.

D. S. KORZHINSKY replied, giving some further explanations of the ore bodies described in Professor Zavaritsky's paper.



# МЕТАСОМАТИЗМ И МЕТАМОРФИЗМ В КОЛЧЕДАННЫХ МЕСТОРОЖДЕНИЯХ УРАЛА.

А. Н. ЗАВАРИЦКИЙ.

Пиритовые метасоматические залежи, находящиеся обыкновенно в зонах метаморфизованных вулканических пород, измененных в зеленокаменные породы и зеленые сланцы, считаются одними из самых типичных метасоматических образований, возникших среди этих метаморфических пород.

Такие месторождения стали известны на Урале около 40 лет тому назад и более 30 лет они изучались. Исследования более южных из них, произведенные в течение последнего десятилетия, существенно изменили взгляды на образование этих месторождений. Было обращено внимание на большую роль более позднего метаморфизма и сопровождающих этот метаморфизм метасоматических процессов. Многие признаки, которые считались указаниями на метасоматическое замещение сланцев, уже сужествовавших ко времени первичного отложения руды, пришлось рассматривать иначе.

Новые факты, указанные на Урале, проливают свет и на происхождение колчеданных залежей вообще, так как некоторые из этих фактов указывались и в других месторождениях земного шара. Новые взгляды могли быть с успехом проверены на Урале вследствие особо благоприятных для понимания этих фактов геологических условий нахождения здесь пиритовых месторождений.

Колчеданные месторождения Урала, за исключением некоторых случайных находок в центральной зоне и на западном склоне, представляют единую группу месторождений, находящихся в сходных геологических условиях в зоне силурийских и девонских вулканических пород.

Как показывают последние исследования в средней части Урала, здесь месторождения колчеданов залегают среди вулканических пород лудлоуского и даунтонского ярусов. На Среднем Урале в конгломератах верхнего силура найдены редкие гальки серицитово-кварцевых пород, обильно импрегнированных пиритом. Эти метаморфические породы похожи на боковые породы колчеданных залежей и рассматривались, как прямое указание на возраст залежей более древний, чем слои, где эти гальки найдены.

Как известно главная эпоха складчатости и появление больших гранитных интрузий на Урале, а также метаморфизм более древних пород относятся здесь к варисскому времени. Вулканические породы, заключающие залежи колчеданов, претерпели воздействие регионального метаморфизма.

На длинном протяжении Урала, где расположены колчеданные месторождения, породы подверглись метаморфизму, интенсивность которого различна как по простиранию всей полосы, так и вкрест простирания. Наиболее интенсивно метаморфизованные породы находятся в Среднем Урале, где полоса вулканических пород, со слоями залегающих в них осадочных, сжата и дислоцирована в наибольшей степени. Здесь вулканические породы превращены в порфиroidы, зеленые сланцы и в большинстве случаев утратили свою первоначальную структуру. В Северном и Южном Урале горные породы не столь интенсивно смяты. Изменения в них слабее и структуры свойственные вулканическим породам: порфировая, офитовая и другие, или туфовая структура, хорошо сохраняются, хотя минералогический состав изменен и отвечает зеленокаменной фации метаморфических пород. В

Южном Урале, в Таналык-Баймакском районе менее метаморфизованные породы заключают узкую полосу более сильно метаморфизованных сланцеватых пород. Еще южнее на самом юге Урала в месторождении Блява рудные тела находятся среди типичных пород спилитовой серии с шаровыми лавами, дайками и силлами кератофиров и с прослоями радиоляритов среди вулканических пород.

Так как степень метаморфизма горных пород, заключающих колчеданные залежи различна, то, если рудные тела действительно были образованы раньше эпохи диастрофизма и метаморфических изменений, они исключительно благоприятные для изучения действия метаморфизма на колчеданные залежи. Они позволяют нам проследить разные степени изменения в связи с разной степенью изменения боковых пород.

Раньше, когда было известно меньшее число месторождений и они были известны только в Среднем Урале, априорно эти залежи считали более молодыми, чем региональный метаморфизм вмещающих их пород, причем различия между месторождениями объясняли разницей в условиях первичного отложения. Время образования колчеданных залежей принималось соответствующим главной эпохе гранитовых интрузий на Урале.

Колчеданные залежи, которые стали известны и описаны в Среднем Урале, залегают среди зеленых сланцев. Таковы, например, известные месторождения Кыштыма.

Открытие месторождений на юге Урала обнаружило ряд отличий их от среднеуральских, и это заставило пересмотреть все другие известные колчеданные залежи. Было показано, что характерные признаки месторождений меняются в зависимости от степени регионального метаморфизма в различных зонах вмещающей толщи вулканических пород. Были обнаружены признаки очевидного метаморфизма и в самих рудных телах в месторождениях Среднего Урала. Поэтому в настоящее время значительное число исследователей уральских колчеданных месторождений пришло к заключению, что здесь мы имеем в различной степени метаморфизованные месторождения одного и того же типа и что многие характерные признаки, которые раньше считали первичными, являются результатом разной степени метаморфизма.

Если пиритовые залежи претерпели метаморфизм вместе с вмещающими их горными породами, то надо ожидать, что такого рода метаморфические процессы имели место и в непосредственно вмещающих рудные тела боковых породах, которые были ранее изменены гидротермальными рудоносными растворами при первоначальном образовании рудных тел.

Там, где можно предполагать действие позднейшего динамического метаморфизма, боковые породы представлены как обычно хлоритовыми и серицитовыми сланцами. В месторождениях, менее метаморфизованных, иногда сланцеватость мало заметна; в некоторых случаях боковые породы—не сланцеватые кварцево-серицитовые породы. Возможно, что первоначальные гидротермальные изменения кроме серицитизации, хлоритизации и развития кварца состояли и в других формах разложения: каолинизации и силицификации, но эти превращения скрыты позднейшим метаморфизмом.

В большинство случаев, однако, под влиянием динамического метаморфизма на горные породы, предварительно измененные гидротермальными растворами, нельзя ожидать резкого изменения минералогического состава: серицит и хлорит остаются минералами устойчивыми и при этих новых условиях и только структура пород подвергается изменению. Интересно в связи с этим отметить, что грубочешуйчатые серицитовые сланцы Дегтярского месторождения 35 лет тому назад Дюпарк считал подобными метаморфическим слюдяным сланцам центральной зоны Урала. Однако, в одном из месторождений Среднего Урала (Рябининская разведка) в серицитовых сланцах вмещающих месторождение были обнаружены метакристаллы хлоритоида. Это может рассматриваться, как указание на стресс при образовании этих сланцев.



Гидротермально измененные породы, повидимому, были менее устойчивыми при региональном метаморфизме. Под влиянием метаморфизма они делались более сланцеватыми и потому после метаморфизма оказалось, что рудные линзы приурочены к зонам более рассланцованным в полосе метаморфических пород. Так как гидротермальные изменения не всегда сопровождаются сульфидной минерализацией, то не все более сланцеватые и более метаморфизованные зоны содержат рудные тела. Это давно было показано разведочными работами но это нельзя теперь рассматривать как признак, указывающий на более позднее образование руд в более рассланцованных породах, или на то, что более рассланцованные зоны были путями рудоносных растворов.

Процессу первичного замещения рудой подвергались, повидимому, различные горные породы: вулканические породы, нередко вулканические туфы и брекчии, в некоторых случаях также и осадочные горные породы. Некоторые рудные тела—в месторождениях Левиха, Сан-Донато, Дегтярка, Кабан—пересечены дайками изверженных горных пород (порфириты), также подвергшихся в большей или меньшей степени динамическому метаморфизму.

Как известно, существует тесная связь между формой колчеданных залежей и характером вмещающих их пород, именно степенью совершенства их сланцеватости. В настоящее время для уральских месторождений мы считаем эту связь результатом динамического воздействия метаморфизма.

Уже давно установлено, что при региональном метаморфизме рудных (особенно колчеданных) залежей форма залежей изменяется вследствие различной компетентности руд и вмещающих пород.

Характерна линзообразная форма, которую принимают более компетентные участки толщи пород подвергающейся метаморфизму. Известно также, что линзообразная форма типична для колчеданных месторождений, залегающих в метаморфизованных сланцеватых породах. Залегая в общем согласно эти линзы как бы раздвигают плоскости сланцеватости, изгибающейся около них. Такие формы рудных тел когда то рассматривались как один из признаков ин'екции сульфидного материала („магмы“) под давлением. С точки зрения метаморфизма залежей вместе с окружающими породами—это указывает на разницу в компетентности руд и пород и объясняется изгибанием слоев сланцев около более прочного рудного тела при внешнем давлении. В некоторых случаях граница рудного тела проходит под углом к общему направлению сланцеватости, но обыкновенно при этом у контакта сланцеватость загибается, идет параллельно контакту. Рудные тела, залегающие среди не сланцеватых менее измененных пород, имеют более неправильную форму; нередко они следуют контактам силлов или дайк с окружающими породами.

Интересно различие между характерной линзообразной формой рудных тел в западной част и Таналык-Баймакского района среди пород рассланцованной зоны и более неправильной формой месторождений восточной зоны этого района.

Другие явные деформации пиритовых залежей также известны в нескольких месторождениях на Урале. Пластообразные залежи в Дегтярском месторождении изогнуты, в местах перегибов раздроблены и отдельные части их иногда перемещены, причем на руде появляются зеркала скольжения. Такие деформации обнаружены и в некоторых других крупных телах.

Сравнивая метаморфизм руд и вмещающих пород необходимо иметь в виду, что силикаты представляют вообще гораздо более прочные минералы. Поэтому можно думать, что при одновременных изменениях горных пород и заключенных в них сульфидных рудных тел в последних должны происходить более значительные изменения. Вещество руд способно к гораздо более легкому перемещению и перекристаллизации. При общем метаморфизме новообразования для рудных минералов и их агрегатов, как можно думать, будут возникать скорее, чем для силикатов вмещающих пород.

Было установлено, что минералогический состав и структура руд месторождений, заключенных среди вулканических пород почти не метаморфизованных (Южный Урал), стличаются от минералогического состава и структуры руд месторождений среди зеленокаменных пород и зеленых сланцев, являющихся продуктами метаморфизма тех же вулканических пород (Средний Урал), также показало различия.

В неметаморфизованных рудах Южного Урала в месторождениях Блява и Яман-Касы на ряду с пиритом существенным компонентом руды является также марказит и иногда землистая разновидность  $\text{FeS}_2$ , которую определяют как мельниковит. Вместе с сфалеритом в таких неметаморфизованных рудах встречается вюртцит.

Очень распространенными в неметаморфизованных и слабо метаморфизованных рудных телах являются коллоформные структуры руд. Именно в таких формах мы находим марказит и вюртцит, образующие почки радиально лучистого строения. Мельниковит встречается в центральной части почек вместе с марказитом или в тонких концентрических зонах. Пирит явно замещает другие дисульфиды железа, а сфалерит—вюртцит. При этом иногда остается заметной коллоформная структура, иногда же руда превращается в зернистый агрегат без заметной правильности в расположении зерен.

В месторождении Сибай коллоформные структуры очень распространены, но здесь совершенно отсутствуют марказит и вюртцит. Однако не редки радиально лучистые формы пирита, быть может, псевдоморфозы его по марказиту.

Когда в сложении коллоформных структур руд принимает участие халькопирит, он чаще всего чередуется в виде тонких зон с пиритом или выполняет трещинки, пересекающие почки. В таком же виде иногда встречается и сфалерит. Среди сфалеритовых и вюртцитовых почек мельчайшие включения халькопирита нередко тоже располагаются зонально.

Перекристаллизация и превращение марказита и мельниковита в пирит, а вюртцита в сфалерит чаще всего происходит с внешней стороны коллоформных образований, но иногда эти минералы развиваются и внутри их.

В настоящее время почти все исследователи колчеданных месторождений Урала принимают марказит и вюртцит в месторождениях Южного Урала Блява и Яман-Касы за более ранние минералы, подвергающиеся перекристаллизации и превращению в пирит и сфалерит. В некоторых рудах с коллоформной структурой встречается кварц в сферических формах тоже напоминающих коллоформные образования опала или халцедона. Вместе с коллоформными структурами руды в еще более значительной степени мы имеем распространенными первичные структуры мелкозернистые, иногда друзовые, но они менее характерны.

В месторождениях Среднего Урала в последнее время также найдены в руде остатки коллоформных структур, подобных тем, какие очень распространены в месторождениях Южного Урала, но здесь такие структуры являются довольно редкими и плохо сохранились.

Нахождение коллоформных структур в уральских месторождениях может рассматриваться как указание на сохранившиеся черты первоначального строения залежей до их метаморфизма.

В рудах месторождений Среднего Урала, залегающих среди метаморфизованных и рассланцованных пород, встречаются обычные структуры, хорошо известные в большинстве пиритовых залежей других стран.

Пирит является минералом образовавшимся ранее других. В тех случаях, когда он является преобладающим, часто видны ясные явления механических воздействий: зерна пирита раздроблены, иногда обломки их смещены; иногда зерна пирита превращены в очки. Структура руды во многих месторождениях напоминает структуру очковых гнейсов. В то же время халькопирит и сфалерит очень редко обнаруживают следы механических деформаций: они полностью перекристаллизованы и отлагались почти одновременно, или заполняя трещинки раздробленного пирита, или метасоматически его замещая.



В некоторых месторождениях, претерпевших наиболее сильный метаморфизм, пирит также перекристаллизован, катакластические структуры отсутствуют и пиритовая руда принимает гранобластическую структуру. Неделимые пирита, несколько удлинённые в направлении сланцеватости, образуют сплошной агрегат, напоминающий структуру гнейсов или некоторых кварцитов. Таковы руды Дегтярского месторождения около висячего бока. Месторождение это залегает среди порфиринов и сланцев.

Известно, что один и тот же минерал, чаще всего кварц, может находиться в метаморфических породах и как реликтовый минерал, сохранившийся от первоначального состава породы, и как новообразование во время процесса метаморфизма. Тогда как в реликтах мы можем наблюдать следы механических воздействий: раздробление, волнистое погасание и т.д., вторичные зерна кварца, образовавшиеся при метаморфизме этого не обнаруживают. Те же черты мы можем видеть и в пирите колчеданных залежей. Тогда как некоторые из его зерен представляются разломанными и раздробленными остатками первичных зерен, другие зерна возникли во время метаморфизма.

В некоторых метаморфических горных породах более прочные минералы, такие как кварц, могут сохраняться, тогда как другие минералы (хлорит, серицит) являются новообразованиями, возникшими при самом метаморфизме. Так же и в рудах наряду с реликтами пирита другие минералы оказываются полностью перекристаллизованными и переотложенными при динамическом метаморфизме месторождений. При этом, как почти при всяком метаморфическом процессе имели место процессы метасоматизма: раздробленные зерна пирита замещались халькопиритом, в силикатовых боковых породах во время метаморфизма росли вкрапленники пирита и других сульфидов, замещая силикатовое вещество породы, образовывались тонкие прожилки и т.д.

Принимая во внимание возраст пирита, замещаемого халькопиритом и частью сфалеритом, некоторые исследователи думали, что халькопирит и сфалерит отлагались во вторую фазу минерализации. Теперь мы считаем, что эти минералы переотлагались во время динамического метаморфизма, которому подвергались месторождения. Пирит, будучи более устойчивым минералом, подвергался преимущественно лишь механическим деформациям, тогда как другие менее устойчивые при метаморфизме минералы были почти полностью перекристаллизованы и переотложены.

Соотношения сульфидов в колчеданных месторождениях Среднего Урала можно сравнивать с последовательностью минералов кристаллобластического ряда в метаморфических горных породах, но не с последовательностью минералов, первично выпадающих из раствора.

Сходство с метаморфическими горными породами в структуре характерно проявляется в рудах относительно богатых легко поддающимися перекристаллизации халькопиритом и сфалеритом. Такие руды очень часто обладают полосчатой структурой, причем чередуются полосы более богатые то халькопиритом, то сфалеритом. После протравливания в отдельных прослоях видна иногда гнейсовидная структура с зернами вытянутыми в одном направлении. В зернах сфалерита и халькопирита при этом иногда появляются тонкие полисинтетические двойниковые пластинки, местами изогнутые, обязанные своим происхождением, очевидно, влиянию давления.

В таких гнейсовидных рудах некоторые крупные зерна пирита выделяются подобно тому, как очки кварца или полевого шпата в очковых гнейсах или порфириодах. Иногда вокруг, таких кристаллов пирита развиваются более крупные, чем в остальной массе зерна халькопирита, образуя венчики или „хвосты“ в тенях давления, совершенно подобно тому, как такие венчики, образованные хлоритом, серицитом или другими минералами метаморфизма, развиваются около подобных очков в метаморфических сланцеватых породах. Это подобие структуры руд структуре метаморфических сланцеватых пород не оставляет сомнения, что и в рудах структурные отношения между минералами обязаны своим происхождением динамическому метаморфизму.

Под влиянием бокового давления на месторождения обыкновенно более мягкие и податливые вмещающие породы предварительно измененные рудоносными растворами приобретали сланцеватость, а в более прочных колчеданных телах появлялись поперечные трещины, которые были заполнены жилками сульфидов более подвижных при метаморфизме: халькопирита, сфалерита, галенита, иногда теннантита вместе с кварцем и баритом. Эти жилки толщиной в несколько сантиметров, выклинивающиеся во всех направлениях, очевидно аналогичны подобным же хорошо известным метаморфическим поперечным жилам и прожилкам, какие встречаются во многих метаморфических сланцеватых породах, пересекая как правило их сланцеватость. Минералогический состав таких жилок близок к составу вмещающих пород; в зеленых сланцах для них характерны альбит, эпидот, кварц; в железистых яшмах—гематит и кварц; в роговообманковых сланцах и амфиболитах—амфибол и плагиоклаз и т.д. Минералогический состав упомянутых поперечных жилок, пересекающих пиритовые рудные тела, также явно находится в связи с составом этих рудных тел.

В некоторых случаях, наоборот, руды, обыкновенно богатые халькопиритом и сфалеритом, являются менее устойчивыми (менее компетентными), чем относительно слабо измененные боковые породы. Тогда руды принимают полосчатую структуру и, наоборот, в боковых породах около рудных тел возникают короткие тонкие поперечные трещины которые заполняются обычно халькопиритом, проникающим в них из рудных тел. Подобные явления хорошо наблюдались в месторождениях у станции Сан-Донато около Нижнего Тагила.

Рост вкрапленников пирита около рудных тел во время метаморфизма и образования сланцев уже давно привлек внимание Де-Манье. Он указывал, что некоторые вкрапленники пирита в боковых породах колчеданных залежей повернуты, и хвосты из табличек серицита или хлорита, возникающие около них при метаморфизме, имеют сигмоидное расположение. Уральские месторождения часто обнаруживают такое соотношение.

При своих исследованиях пиритовых кристаллов из уральских рудных месторождений С. Н. Иванов применил метод травления электрическим током. Это обнаружило важную особенность в структуре пиритовых зерен из колчеданных залежей. При травлении они обнаруживают многочисленные тонкие зоны роста пиритовых кристаллов из менее метаморфизованных месторождений. Но эта зональность как будто бы исчезает при позднейшей перекристаллизации. В центральной части кубиков пирита вкрапленных в боковые породы встречаются только ядра имеющие очертания пиритоэдров с ясным зональным строением.

Пиритоэдры ядер возможно представляют кристаллы, образовавшиеся при несколько отличающихся условиях, чем кубы, представляющие последнюю стадию образования кристаллов. Кажется вероятным, что эти кубические кристаллы росли при новых условиях во время метаморфизма, когда первичные пиритоэдры превращались в кубы. Следует отметить, что в тех уральских колчеданных месторождениях, которые по их геологическому положению следует рассматривать как сильно метаморфизованные, пиритовые кристаллы находятся только в кубах. В менее метаморфизованных телах появляются также пиритоэдры.\*

Тот факт, что некоторые кристаллы пирита, вкрапленные в боковой породе, несомненно росли во время метаморфизма, дает основание думать, что и вторичная импрегнация пирита, и вторичные жилки или скопления этого минерала могли быть обычными явлениями при метаморфизме. Интенсивность вторичной вкрапленности пирита, возникающей при метаморфизме, не всюду была одинакова, но различалась в различных условиях. Подобно тому, как некоторые метаморфические минералы охотно развиваются около метакристаллов, в гораздо большем масштабе по размерам благоприятные места для образования метаморфических минералов и их агрегатов могут появиться у концов рудных тел по направлению

\*Пиритоэдры пользуются гораздо большим распространением в кавказских месторождениях не подвергшихся в такой степени метаморфизму как месторождения Урала. Месторождение Чирагидзор на Кавказе интересно почти полным отсутствием кубических кристаллов пирита.



простираения. Подобным образом можно объяснить появление характерных хвостов густой окраски пирита у быстро выклинивающихся концов рудных тел в направлении простираения вмещающих их сланцев.

Очень трудно оценить размеры перемещения рудного вещества, но переотложения и метасоматические замещения других минералов, наверное, при метаморфизме имели место. Поэтому метасоматическое замещение одного минерала другим или даже образование таким путем отдельных небольших аккумуляций рудных минералов никак не могут служить доказательством одновременного с ними первичного отложения всей руды. Они могли происходить при метаморфизме.

Признаки, указывающие что рудное вещество отложилось в уже метаморфизованных боковых породах, здесь не убедительны. Так например, нахождение тонких пиритовых прожилков, пересекающих боковые породы около рудной залежи, считается как довод в пользу одновременного с их образованием эпигенетического отложения всей рудной залежи. Но такие прожилки могли возникнуть позднее при метаморфизме за счет вещества залежи. Такие прожилки могут пересекать сланцеватые боковые породы, но сланцеватость этих пород вместе с тем может быть возникшей после отложения главных рудных залежей, подвергавшихся при этом метаморфизму вместе с вмещающими породами.

Некоторую аналогию мы можем найти в хорошо известных и уже упоминавшихся примерах метаморфических жилков в метаморфических сланцах. Образование таких прожилков считается одновременным с метаморфизмом. Таким же путем могут образоваться даже небольшие рудные тела сопровождающие главную залежь.

Во время метаморфизма миграция вещества и переотложение должны были привести к новому распределению металлов в залежах и так могло возникнуть новое распределение обогащенных медью и цинком участков в рудном теле.

При региональном метаморфизме различие в условиях отложения руд в разных частях рудных тел, вероятно, зависит прежде всего от разницы в давлении, которая зависит, повидимому, от формы этого тела. Таким образом, форма рудного тела может воздействовать распределению переотложенных металлов. В колчеданных залежах существует определенная связь между содержанием более редких металлов и очертаниями рудного тела. В Дегтярском месторождении, например, выяснено, что относительно обогащены сфалеритом и халькопиритом краевые (внешние) части залежи, как в направлении простираения, так и вглубь. Кроме того, количество этих минералов несколько увеличивается у лежащего бока. При этом руда приобретает полосчатую структуру и в ней можно наблюдать замещение пирита сфалеритом. Кажется, что характерное обогащение медью более тонких частей рудных линз, постоянно наблюдаемое в пиритовых залежах, могло зависеть от этой причины.

Так как до недавнего времени на Урале, как и в других областях, особенности минералогического состава руды рассматривались только как признаки различных физических условий первичного отложения и возможность изменения состава при метаморфизме упускалась из виду, то мало обращалось внимания на те факты, которые с новой точки зрения могли осветить парагенезис минералов, и которые наблюдались и отчасти были описаны в рудниках выработанных и теперь заброшенных.

Минералогический состав пиритовых залежей, как известно, вообще очень однообразен и сравнительно немногие минералы являются существенными составными частями руды. Упомянутые марказит и вюртцит, найденные в наименее измененных месторождениях Южного Урала, являются исключительными, хотя очень характерными. Пирит, в некоторых случаях пирротин, относительно небольшие количества халькопирита и сфалерита, являются более или менее постоянными составными частями. Такие минералы, как теннантит и тетраэдрит, арсенопирит, магнетит, первичный борнит, энаргит, фаматинит, кубанит,

самородное золото и теллуриды золота были встречены в уральских месторождениях как редкие минералы, или как случайные.

При таком однообразии минералогического состава почти невозможно подметить различия в парагенезисе минералов в месторождениях не метаморфизованных и метаморфизованных (за исключением упомянутых марказита и вюртцита). До сих пор блеклые руды наблюдались преимущественно в метаморфизованных колчеданных месторождениях Урала, наоборот, энаргит был встречен в месторождениях не метаморфизованных или слабо метаморфизованных. Интересно поведение самородного золота, частицы которого, чрезвычайно тонкие в месторождениях не подвергшихся метаморфизму, становятся крупнее в месторождениях метаморфизованных.

Мы уже упоминали о дайках пересекающих рудные тела. Можно было бы ожидать явлений метаморфизма в контактах. Однако они еще недостаточно изучены.

Однако, могут быть указаны некоторые интересные факты. Так в упоминавшихся колчеданных залежах около станции Сан-Донато к северу от города Тагила наблюдаются дайки андезитового порфира (порфирита), пересекающего рудное тело. В контактах пиритовая руда значительно обогащается магнетитом, отсутствующим в руде вдали от контакта. Все месторождение подверглось региональному метаморфизму, не очень интенсивному, судя по сохранению местами реликтов первичной коллоформной структуры руды. Некоторые исследователи справедливо, как мне кажется, полагают, что первоначально в контакте с дайками пиритовая руда вероятно была превращена в пирротиновую, а при более позднем динамическом метаморфизме ассоциация пирит + магнетит оказалась более устойчивой, чем пирротин.

В более северном месторождении Кабан имеется несколько залежей. Одни из них заключены среди мягких сланцев, другие в твердых порфиритах (метаандезитах). Те и другие пересечены дайками основных порфировых пород. В руде месторождений, находящихся в сланцах, обнаружены заметные признаки метаморфизма. Характерно образование прорастания халькопирита и борнита в форме реакционных кайм на границе зерен этих минералов. Они напоминают те искусственные прорастания между этими минералами, которые были получены Шварцем. Залежи, заключенные в вулканической породе, в более слабой степени метаморфизованы, и в руде сохранились реликты коллоформных структур.

Измененные боковые породы Кабанских месторождений своеобразны: они часто представлены богатыми кварцем кварцево-серицитовыми породами с андалузитом, диаспором, корундом и зунитом.

Образование колчеданных залежей Урала, как и других им подобных, не может считаться еще выясненным во всех деталях, но идея о метаморфизме этих месторождений позволяет внести порядок в разнообразие их, обнаруженное в последние годы. Это разнообразие создано не столько различиями в условиях первичного метасоматического отложения сульфидов залежей, сколько разной степенью их метаморфизма и разнообразием метасоматических явлений при этом метаморфизме.



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# MAGNESIUM METASOMATISM IN DOLOMITE FROM LUCERNE VALLEY, CALIFORNIA

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## ABSTRACT

A small, isolated, rock-knob forms a prominence above the detritus-strewn desert surface of Lucerne Valley, California. It exposes a series of metamorphic rocks intruded by biotite-tonalite and by minor garnet-aplite dikes. The dominant formation in the metamorphic series is a brucite-marble. Thermal metamorphism seems inadequate to account for the relatively high ratio of MgO to CaO found in some facies of this rock. Formation of brucite by hydrothermal processes appears likely. Additional evidence favouring a hypogene source of magnesite is provided by veins of magnesite, possibly pseudomorphous after nematolite, which cut the brucite-marble.

## INTRODUCTION AND ACKNOWLEDGMENTS

IN December, 1946, Mr. R. M. Richter, of the Marter Mining Company, and Mr. R. S. Lamar, of the Sierra Talc Company, knowing of my interest in high-magnesia rocks, acquainted me with an occurrence in Lucerne Valley, California, which was then undergoing some preliminary development by the Marter Mining Company.

The dominant rock at this locality closely resembles predazzite, a rock type so rare in the United States that a new occurrence seemed immediately to warrant study, particularly as anticipated economic developments gave promise of revealing many of the uncertainties of the geological relationships. These developments are under way, and the studies are in progress. The present report therefore is given primarily to call attention to certain unusual features of the occurrence and their bearing on the problems of magnesite metasomatism, with the hope of eliciting discussion and comparison.

The deposit is of interest because it represents the newest and possibly one of the larger of the less than a half-dozen recorded occurrences\* of predazzite-like rocks in the United States; because portions of the "predazzite" are brucite-dolomite rather than brucite-calcite rock; because of the association of veins of magnesite with the deposit; and because of recently discovered industrial applications for this uncommon mineral association, now being marketed under the trade name of "Lucernite."

In May, 1947, the Field Geology class of the California Institute of Technology under the direction of my colleague, Dr. R. H. Jahns, selected this locality, because of an appropriate combination of topographic simplicity and geological complexity, for an exercise in topographic and geologic mapping. To this group I am indebted for the topographic base and for much of the geology shown in Fig. 1. To Joan Rounds I am grateful for preparing this map from the field original.

To Mr. R. M. Richter I am indebted, not only for the introduction to this interesting occurrence, but for helpful discussion and for free access to private reports upon, and analyses of, the deposit.

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\* Other occurrences reported in the United States are :

Philipsburg, Montana, reported by Emmons and Calkins, (1913, p. 157).

Riverside, California—predazzite is found in three quarries in this vicinity : City quarry, Crestmore quarry, Jensen quarry, all of which are regarded as representing essentially a single occurrence—reported by Rogers, (1918 and 1929), and Woodford, Crippen and Garner, (1941, 354-56).

Mountain Lake Mine, Utah, reported by Rogers, (1918, p. 585).

Organ Mountains, New Mexico, reported by Dunham (1935 and 1936), and Hunt and Faust, (1937).



## CAMPBELL : MAGNESIUM METASOMATISM

### PREVIOUS GEOLOGICAL WORK AND HISTORY OF THE DEPOSIT

The deposit lies in the SE 1/4 of the SE 1/4 of Section 15, T 6 N, R 1 W, San Bernardino base. This is an area not covered by any topographic sheet and in which the geology is practically unknown. The only published information is that in the reconnaissance water-supply paper by Thompson (1929, pp. 610-624). Lucerne Valley is a broad northerly trending trough covered by alluvial fans built out from the bordering Granite Mountains to the west and the Ord Mountains to the east. A playa lake occupies the lowest portion of the valley. A few isolated rock hills, bearing some resemblance to inselbergen, project through the alluvium. In one of these, not far from the north-east border of the playa and about six miles north of Lucerne Valley Post Office, the brucite-marble\* is found.

The deposit was first located, as a potential source of magnesite, in 1940 by Mr. R. M. Richter, at that time engaged in a survey of building stone. It was examined briefly in 1942 by the late Dr. C. F. Tolman for the Kaiser Steel interests. However, the magnesite occurrences are limited, and the property lay idle until after the war when, the value of the brucite-marble in special types of filler having been demonstrated, the current development started.

### GEOLOGY OF THE DEPOSIT

The geological relationships at the deposit are shown, somewhat simplified, on the map in Fig. 1. Vegetation is scant, but talus covers most of the hill, obscuring the actual extent and relationship of the rocks.

The most prominent rock, both because it occupies the crest of the hill as well as portions to the north and south, and because it has a distinctive pitted appearance, is the brucite-marble. Associated with the brucite-marble and best exposed at the south end of the hill in what may be a conformable relationship, are fine-grained, porphyroblastic granulites. Both brucite-marble and granulites are thoroughly recrystallized, and original features have been largely or wholly obliterated. Nevertheless, faint structures—textural variations, contacts, etc.—show a more or less consistent trend of N 70° W, with dips vertical or steep to the south-west.

Thin stringers of metabasalt are also best exposed at the south end of the hill. Attitudes suggest a sill-like relationship, though locally cross-cutting, with the brucite-marble and the granulite.

All three of these rocks (marble, granulite, and metabasalt) have been invaded by tonalite which crops out principally on the northern part of the hill, but is found also in a few small protuberances to the south, suggesting that at depth it may be more extensive. One or two small dikes of aplite occur, and are probably later than the tonalite.

Magnesite veins, too small to show on the geologic map, cut the brucite-marble in many places. These veins vary from tiny stringers to a few veins a foot or more in width. They pinch and swell, change strike and dip within short distances, and are distributed in a very irregular pattern.

### PETROGRAPHY

*Brucite-marble.*—Fresh specimens of the brucite-marble are difficult to obtain for the brucite tends to alter to hydromagnesite, this in turn leaches out, and the characteristic pitted rock is left to make up the bulk of the surface exposures and talus blocks. This alteration, often exhibiting a rude concentric pattern, extends irregularly to depths of at least several feet, or as far as present development has exposed the rock.

The brucite (or the pits representing its former presence) is rather evenly distributed throughout the marble in spheroidal to irregular-shaped granules ranging up to six millimeters in diameter and averaging between one and two millimeters. The granules are notably coarser therefore than those

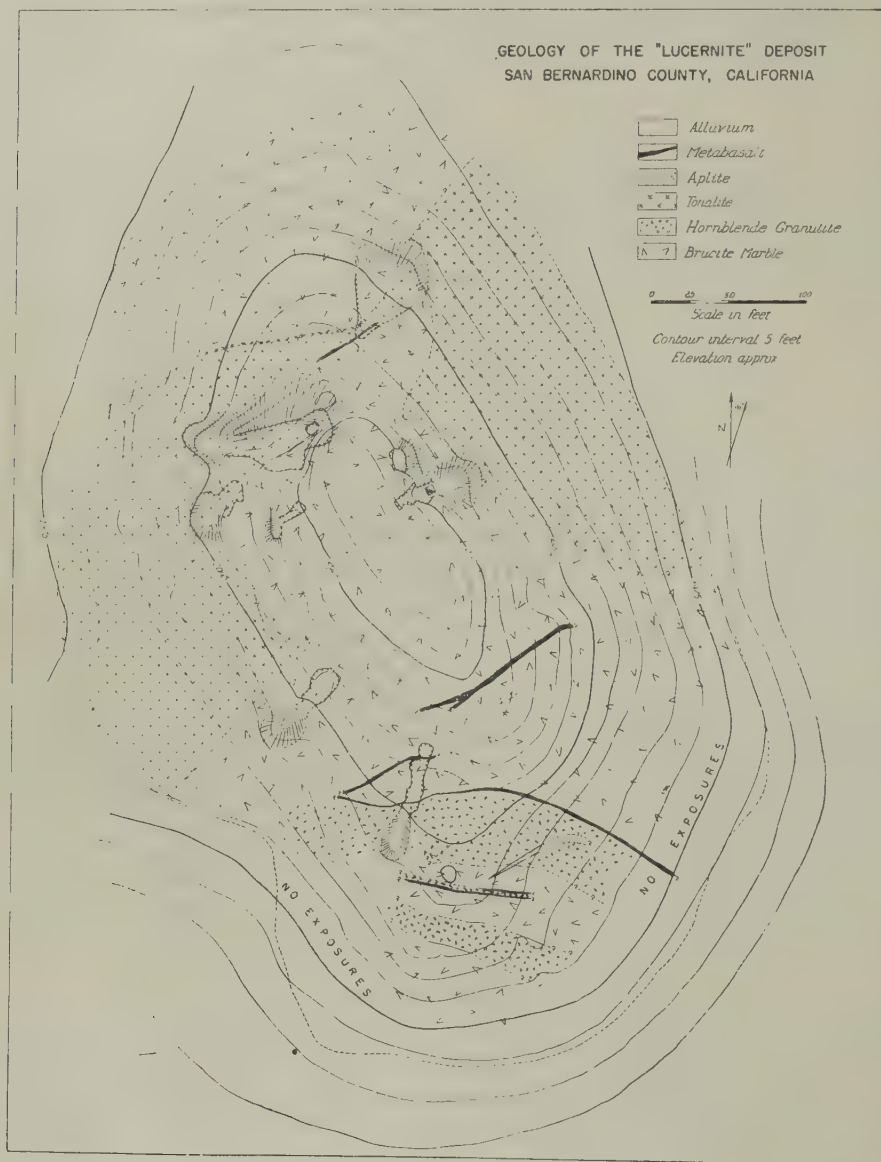
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\* Inasmuch as it cannot yet be determined whether this rock is a pencatite or a predazzite, I shall use, following Watanabe (1935), the somewhat noncommittal term "brucite-marble," and trust that it may acceptably include both brucite-calcite and brucite-dolomite phases, and in whatever range of proportions they may obtain.

### PART III: METASOMATIC PROCESSES IN METAMORPHISM

of the type locality at Fassathal, in the Tyrol. Throughout the range of grain size, the proportion of brucite remains within rather narrow limits, from a minimum of 38 per cent to a maximum of 44 per cent by volume, based on Rosiwal measurements on smoothed surfaces. The average is slightly higher than the theoretical value of 39.6 per cent given for penicatite by Watanabe (1935, p. 57).

In thin sections many of the brucite granules show the scaly concentric pattern commented upon





# CAMPBELL : MAGNESIUM METASOMATISM

Staining tests have not yet been employed, because of lack of sufficient fresh material, and the identity of the associated carbonates has been established largely by index of refraction tests on grains gouged from sawn surfaces. Both calcite and dolomite may occur, even within a single small specimen. Although in some cases dolomite occurs to the exclusion of calcite, the latter appears to be the predominant carbonate. Crystals form an irregular mosaic, as seen in thin section, and range from 0.1 millimeter to 2.0 millimeters in diameter. Many grains exhibit slightly biaxial interference figures. The crystals are commonly clouded with opaque dust-like inclusions, thus resembling those described by Watanabe (1935, p. 54), and Hunt and Faust (1937, p. 1153).

Forsterite grains, up to 0.1 millimeter in diameter, and associated serpentine-like alteration products have been identified in a few specimens, although on the whole the brucite-marble is remarkably free of other minerals.

The only chemical analyses available were made for commercial tests prior to the present study and represent bulk samples rather than analyses of selected specimens. For such value as they may have, a range of representative analyses is given in Table I below.

TABLE I.

	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>
	%	%	%	%
SiO <sub>2</sub> .....	0.12	2.73	1.45	1.25
Al <sub>2</sub> O <sub>3</sub> .....	0.68	0.57	0.77	0.46
Fe <sub>2</sub> O <sub>3</sub> .....	0.18	0.14	0.05	0.13
CaO.....	31.00	32.08	29.20	28.37
MgO .....	20.80	19.68	22.00	22.62
SO <sub>3</sub> .....	—	—	—	0.02
Ignition Loss ...	47.00	45.09	46.25	47.00
	99.78	100.29	99.75	99.85

*A* = "North side top, dolomite," February 28th, 1941.

*B* = January 18th, 1943.

*C* = "Speckled material," August 22nd, 1940.

*D* = "Sample No. 1, W. B. Tucker," June 18th, 1943.

All analyses made by Smith-Emery Company, Los Angeles.

In evaluating these analyses it should be borne in mind that the low-magnesia analyses may represent rock largely leached of its brucite content, while on the other hand the high-magnesia analyses may represent material which has included a part of a magnesite vein. Nevertheless the analyses do indicate that the rock is remarkably low in insolubles and that the MgO:CaO ratio is in several cases significantly higher than that demanded for dolomite (or pencatite).

*Hornblende-granulite*.—This curious rock exhibits a fine-grained to porphyroblastic texture. The porphyroblasts consist of poikiloblastic green hornblende in grains up to 0.8 millimeter in length and of glomeroblastic aggregates of andesine up to 1.0 millimeter in diameter. The matrix consists of an exceedingly fine-grained (averaging about 0.02 millimeter in grain diameters) mosaic of albite and quartz, with minor amounts of green hornblende crystals whose subparallel arrangement gives a faint lineation to the rock. Traces of biotite, apatite, and magnetite occur. Whether this rock was originally igneous, sedimentary, or pyroclastic is not known. Its significance for the present study is perhaps to suggest that, because of the absence of garnet on the one hand and the presence of only traces of biotite on the other, as well as because of the very fine and somewhat variable grain size, it has been subject to only low to moderate metamorphic influences.

*Metabasalt*.—The metabasalt is an extremely fine-grained (average grain diameters are around 0.02 millimeter), somewhat granulose aggregate consisting chiefly of green hornblende, with smaller amounts of pyroxene (diopside?), epidote, and plagioclase. It might indeed be called a hornblendite.

### PART III : METASOMATIC PROCESSES IN METAMORPHISM

Despite the recrystallization it has undergone, chilling phenomena can be recognized at contacts; it therefore seems likely that the rock was originally an intrusive basalt.

*Tonalite*.—The tonalite is a typical medium-grained biotite-tonalite in which the minerals show little more than incipient alteration (principally sericitization of plagioclase). Calcic andesine, quartz, and green biotite are the chief components. Orthoclase, magnetite, apatite, and sphene are present as accessories. The tonalite is relatively free from inclusions and exhibits no changes either of texture or of composition at the approach to contacts other than, very locally, a small amount of serpentinization. Significant linear or planar structures appear to be lacking.

*Aplite*.—The aplite is also a normal type, consisting of a fine-grained mosaic of quartz, microcline, and albite, with minor amounts of garnet and traces of biotite, muscovite, magnetite, and apatite. Like the tonalite, the minerals show little or no evidence of hydrothermal alteration or weathering.

*Magnesite veins*.—The magnesite veins and veinlets exhibit the chalky-white, porcelaneous appearance characteristic of the so-called "amorphous" variety of this mineral. It is, of course, crystalline, but the grains are so small that thin-section study yields little information other than that the crystal dimensions are of the order of 0.01 millimeter or less. A striking feature of most of the magnesite veins is an apparent cross-fibre structure. Yet the fibres cannot be split out as such, and thin sections yield no indication of an aggregation or orientation that would correspond to the fibrous development. The impression is gained that the magnesite is pseudomorphous after some naturally fibrous mineral which has presumably been completely replaced since it has not yet been found in the veins. Of the various possibilities, nematolite (the fibrous variety of brucite) would seem the most likely to have been replaced. It is to be hoped that evidence on this intriguing possibility may some day be found, for although brucite has been known to vein and replace magnesite, the reverse relationship is exceedingly rare.

#### COMPARISON OF THE LUCERNE VALLEY BRUCITE-MARBLE WITH OTHER OCCURRENCES OF THIS TYPE

From the preceding discussion it will be apparent that the Lucerne Valley brucite-marble is similar in many ways to several described occurrences of predazzite-like rocks. In some respects it differs from most of these: (1) periclase has not been found; (2) the MgO:CaO ratio is, locally at least, higher than that required by dolomite or pectatite; (3) magnesite veins, in distinctive fibrous (or pseudo-fibrous) structure, occur in cross-cutting relationship to the brucite-marble. With respect to (1) and (2), Keith (1946) has recently provided an excellent description of brucite-marbles in the Rutherglen district, Ontario, in which periclase is absent and in which high-magnesia facies occur. This latter problem will be discussed further below. With respect to (3), Dunham (1935, pp. 104 and 236) described from the Organ Mountains, New Mexico, the conversion of brucite-marble to magnesite. This seems to have been a wholesale replacement and is thus rather different in form, though perhaps not in time or in substance, from the magnesite veins in the Lucerne Valley occurrence.

An explanation of high-magnesia facies leads to some interesting considerations. Goudge (1939, p. 9) and Keith (1946, p. 979) have presented three hypotheses: (1) that the rock was originally a magnesian dolomite; (2) that subsequent to dedolomitization and formation of brucite, there was dolomitization of the calcite; or (3) that some brucite (or the MgO to form it) was introduced by the intrusive or by dissociation of dolomite at contacts. Goudge somewhat favored the second hypothesis; Keith preferred the third.

In the Lucerne Valley deposit, the even distribution of the brucite granules in the marble, apparently uncontrolled by channelways or proximity to intrusives, certainly argues for the classic explanation of predazzite. This assumes dedolomitization resulting from thermal metamorphism, with subsequent hydration of the newly formed periclase, yielding a brucite-marble in which the ratio of MgO to CaO will be the same as in the original rock (1 to 1, if the rock was a pure dolomite). No doubt this process can account for the bulk of the brucite in the deposit. Where higher magnesia ratios prevail I am inclined to favour Keith's hypothesis (3, above) because of some textural characteristics shown by the brucite granules (that is, veining and possible replacement of calcite by brucite), and because



of the evidence provided by the magnesite veins that magnesia-rich solutions were traversing the rocks subsequent to the major thermal metamorphism.

If it be assumed that there has been limited introduction of magnesia, there are several possibilities to consider, any of which can account for MgO:CaO ratios higher than the 1:1 of dolomite and pentacite:

(1) The introduced magnesia may have entered a pure pentacite, dolomitizing the calcite. In such case, the resulting rock would be a brucite-dolomite, and the volume relations of brucite to carbonate would be essentially the same as in pentacite.

(2) The introduced magnesia may have entered a pure pentacite, contributing to renewed or additional growth of the brucite with resulting replacement of calcite by brucite. In such case, the resulting rock would be a brucite-limestone, and the volume relations of brucite to carbonate would show a ratio higher than in pentacite.

(3) The introduced magnesia may have entered a rock in which dedolomitization had been incomplete and, as in (1) above, dolomitized such calcite as had formed, thereby yielding a brucite-dolomite in which volume relations of brucite to carbonate would be less than the ratio in pentacite. Or, the introduced magnesia may have contributed to new growth of brucite, as in (2) above, with partial replacement of calcite, or dolomite or both, thus yielding a brucite-dolomite-calcite rock in which the volume relations of brucite to carbonate might be either the same or more or less than in pentacite.

It is to be hoped that sufficient fresh material may become available to permit the careful correlation of chemical with quantitative mineralogical analyses that should enable a selection to be made from among the possibilities outlined.

#### AGE OF THE ROCKS

There is no direct indication of the age of the rocks involved in this deposit. Woodford, Crippen, and Garner (1941, p. 353) tentatively date the Crestmore predazzite as upper Paleozoic. Vaughn (1922) in his study of the San Bernardino Mountains which lie some five to ten miles south of Lucerne Valley, dates a thick sedimentary section which includes some limestones, as probably early Paleozoic, and the associated granitic intrusives as probably late Jurassic. Based therefore only upon the tenuous evidence of lithologic similarity and geographic proximity, the Lucerne Valley brucite-marble is perhaps Paleozoic and the granodiorite probably late Jurassic.

#### SUMMARY AND CONCLUSIONS

A brucite-marble in Lucerne Valley, California, is notable for the apparent lack of associated periclase, for some relatively high-magnesia facies, and for the presence of cross-cutting magnesite veins, perhaps pseudomorphous after nematolite.

The formation of the brucite-marble may well have followed very largely the classic explanation: dedolomitization, with formation of periclase, and subsequent hydration of periclase to form brucite. The apparent absence of periclase, however, lends some support to the suggestion of Brown (1943) that brucite may form directly by elimination of CO<sub>2</sub> and substitution of H<sub>2</sub>O, in a single reaction. There is, moreover, some evidence substantiating the hypothesis advanced by Keith (1946) favouring introduction of magnesia and formation of the brucite, in part at least by replacement. The possible concomitants of such an assumption are considered, and the mineral-volume relationships which might distinguish the various possibilities are pointed out.

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### DISCUSSION

DORIS L. REYNOLDS asked if it were not possible that the magnesium enrichment of the dolomite was a basic front formed in relation to the tonalite. If the tonalite had been formed by replacement of dolomite then Mg, Ca and CO<sub>2</sub> must have been displaced, and the Mg and Ca might have been fixed differentially within the rocks of the surrounding aureole.

I. CAMPBELL in reply said that Dr. Reynolds had made a very interesting suggestion, and he would make a point of re-examining the tonalite to see if any relict structures or evidence of a replacement origin were to be found.



# THE GENESIS OF SILLIMANITE AND KYANITE ROCKS BY ALUMINA METASOMATISM

By A. R. ALDERMAN

Australia

## ABSTRACT

Sillimanite- and kyanite-rich rocks cut across the strike of a series of schists and other metamorphic sediments near Williamstown, South Australia. Evidence is presented supporting the interpretation that the aluminous rocks were derived from the enclosing schists by metasomatism due to the passage of alumina-rich fluids. The sequence of rock types and mineral changes produced during a period of rising and falling temperatures is listed and it is noted that ions of increasing radii entered into the reactions as the sequence progressed.

THE occurrence in South Australia, near Williamstown, of rocks rich in sillimanite and kyanite has already been described.\* Briefly, these rocks occur over a limited area and are surrounded by rocks of a comparatively low degree of metamorphism and of Proterozoic age. These surrounding rocks are metamorphosed sediments and consist of biotite-schists, marbles and quartzites. They do not appear to be separated from the sillimanite-kyanite rocks by any major structural feature. The aluminous rocks cut directly across the strike of the metamorphosed sediments from which, the field evidence suggests, they were derived.

It has already been suggested (*loc. cit.*) that the conversion of the schists of varied composition into rocks rich in sillimanite and kyanite was accomplished by metasomatic processes in which alumina-rich fluids played the leading part. The field relations of the rocks, the texture of the rocks themselves and other evidences of the activity of alumina-rich fluids all support the alumina-metasomatism theory.

In its later stages, and presumably with falling temperature and lower alumina-concentration, the metasomatic process gave way to pegmatization and, still later, to hydrothermal activity in which much of the sillimanite was converted to clay, and kyanite to muscovite.

At the focal point of the metasomatic activity the rocks consist essentially of sillimanite and quartz with subordinate rutile, although a small amount of kyanite is often present. This innermost region is surrounded by an ill-defined zone of massive kyanite-quartz-(rutile) rocks. These, in turn, pass outwards into knotted red-stained biotite-schists in which shimmer-aggregates almost certainly represent former kyanite crystals. The sillimanite-quartz and kyanite-quartz rocks represent regions in which solution of the other bases (Ca, Mg, Fe, etc.) in the pre-existing rocks accompanied precipitation of aluminium silicate, whereas in the biotite-(kyanite)-schists solution did not keep pace with precipitation.

The massive sillimanite-quartz rocks frequently contain small patches of quartz and kyanite which may have been formed by migration of aluminium silicate under conditions of falling temperature. In other cases it is obvious that kyanite has been formed before the sillimanite into which it is inverting. Whether this indicates that all the sillimanite has, with rising temperatures, been formed by the inversion of kyanite is uncertain. What does seem likely is that the conditions, for example the presence of solvent fluids, would have favoured the acceleration of the otherwise sluggish kyanite-to-sillimanite inversion. The kyanite in the massive kyanite-quartz rocks typically shows resorbed outlines although the solution products are not, in this case, present.

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\* A. R. ALDERMAN. *Trans. Roy. Soc. S. Austr.*, 66, (1), 1942, p. 3.

### PART III: METASOMATIC PROCESSES IN METAMORPHISM

It is certain that much kyanite has been formed later than sillimanite, a fact proved by the presence of definite veins of kyanite, and its alteration products, cutting through massive sillimanite-quartz rock. Large masses of kyanite are also found in the knotted (former kyanite) biotite-schists. Although, owing to poor exposures, the relations here are not very clear it appears likely that the massive kyanite occurs as segregations in the schists. Small crystals of corundum are frequently associated with the kyanite and its degradation products.

Some of the quartz-kyanite veins contain a considerable amount of feldspar (oligoclase) and can be classed as kyanite-pegmatites thus providing an intermediate state between the high-temperature sillimanite-quartz and kyanite-quartz rocks and the low-temperature normal pegmatite. These normal pegmatites (quartz-orthoclase-muscovite-biotite) are abundant in the surrounding area and have tourmaline as their main accessory mineral.

At still lower temperatures more or less normal hydrothermal processes were active and resulted in the conversion of much of the sillimanite into clay. Kyanite was similarly converted to pale-green muscovite which seems to conform to the variety *damourite*.

The main rock-types and their genesis can be interpreted as in the following summarizing table. In this table the term "sequence" is not used to denote time entirely but rather a factor in which time is involved as well as change of temperature and of aluminium concentration. Presumably more than one stage in the sequence could have been active simultaneously.

Sequence	Rock Types	Temperature and aluminium concentration	Genesis	Accessory Minerals	Active Substances
1	Massive kyanite—quartz	rising	metasomatic	rutile (tourmaline)	(B), Si, Al, Ti
2	Massive sillimanite—quartz	maximum	metasomatic	rutile (tourmaline)	(B), Si, Al, Ti
3	Massive kyanite—quartz	falling	metasomatic	rutile (tourmaline)	(B), Si, Al, Ti
4	Kyanite—quartz veins	falling	precipitation	rutile (tourmaline)	(B), Si, Al, Ti
5	Kyanite schists	falling	permeation	rutile (tourmaline)	(B), Si, Al, Ti
6	Kyanite pegmatites	falling	precipitation	rutile, biotite (tourmaline)	(B), Si, Al, Ti, Fe''', Mg, Fe'', Na, K
7	Pegmatites	falling	precipitation	tourmaline, muscovite, biotite	B, Si, Al, Fe''', Mg, Fe'', (Na), K, OH
8	Clay, muscovite	falling	permeation	tourmaline(?)	B(?), Si, K, OH

The order of appearance and disappearance of active substances during the sequence is interesting. Silica and, to a much smaller extent, boron were active during the whole sequence. The order for the other ions is Al, Ti, Fe''', Mg, Fe'', Na, K, OH.

The radii of these ions in Å units are:

B	Si	Al	Ti	Fe'''	Mg	Fe''	Na	K	OH
·22	·39	·57	·64	·67	·78	·83	·98	1·33	1·33

It is noted that larger and larger ions enter into the reactions as the sequence progresses.

Brief mention has been made of the conversion, under hydrothermal conditions, of much of the sillimanite to clay and of kyanite to muscovite. The kyanite-to-mica conversion has already been described (*loc. cit.*). The clay produced from sillimanite seems to consist largely of kaolinite although there are some indications that dickite has also been formed. Diaspore is frequently also present in the clay assemblage which is being further examined.

The writer wishes to thank Professor C. E. Tilley for his most helpful interest in the subject of this paper.

#### DISCUSSION

THE CHAIRMAN, H. VON ECKERMANN, said that the metasomatic alteration of sillimanite into clay might not be uncommon in the migmatites around the Alnö alkaline intrusion, where for instance, the sillimanite was altered into montmorillonite.



# A DEMONSTRATION OF THE GRANITIZED ROCKS OF NAMAQUALAND

(Illustrated by Coloured Lantern Slides)

By L. T. NEL

South Africa

**I**N summary of his demonstration Dr. Nel wrote as follows: "A series of coloured lantern slides of manuscript geological sheets was shown with the object of drawing the attention of geologists to extensive exposures of granitized rocks in Namaqualand, South Africa. The geological sheets cover a belt of country along the Orange river several thousand square miles in extent and stretching from Upington westwards for about 300 miles.

The area is underlain by granites, gneisses and metamorphosed strata of Archæan age. Owing to arid, or semi-arid, conditions there is little or no vegetation, and rock formations are therefore exposed continuously over wide tracts of country. In fact many of the aerial photographs used to survey the country geologically are essentially monochrome geological maps of particular localities. Below the Aughrabies Falls the country is deeply dissected and in places the crests of mountains may rise to a thousand feet or more above the floors of deep gorges.

Various types of granites and gneisses are present. Some of them appear to be metamorphosed strata granitized in place whilst others, especially those with transgressive relationships, have been interpreted by some geologists concerned as of magmatic origin. Contacts may be sharp or transitional. Pegmatites and aplites occur in great profusion in all the rock types of the area. They have transgressive relationships to the country rocks and their emplacement occurred at a late stage. Mineralization is often associated with the pegmatites, and minerals such as wolframite, scheelite, cassiterite, molybdenite, euxenite, bismuthinite, beryl and tourmaline occur sporadically in them or close to their contacts.

The stratigraphic rocks involved in the process of granitization belong chiefly to the Kaaie and Marydale Series of the Kheis System, which is a succession of arenaceous rocks (including arkoses), argillaceous rocks, limestones, and lavas with associated dolerites, gabbros, norites, picrites and pyroxenites in the Marydale Series. These rocks show all stages of metamorphism until their original character has become obliterated. They would appear to provide a gradual transition from stratified rocks into granites or granite-looking rocks.

The structural pattern of the area is complicated. Broadly speaking it is that of a highly folded region in which there are a number of alternant anticlines and synclines in an echelon arrangement. The limbs are sometimes further folded in the anticlines to form smaller subsidiary folds. These structures are often arranged around circular or ovaloid-shaped domes.

In Namaqualand, therefore, there are beautifully exposed on a large scale a series of granites, gneisses and highly metamorphosed stratigraphic rocks which, it seems, could provide much of the evidence needed for a satisfactory solution of the problem regarding the origin of granites. It is hoped that their occurrence may entice investigators in the field of petrogenesis to visit South Africa in order to study the phenomena revealed in the Namaqualand exposures."

# QUELQUES REMARQUES SUR LE PROBLÈME DU GRANITE ET SUGGESTIONS EN VUE DE L'ORIENTATION DES TRAVAUX DU PROCHAIN CONGRÈS

Par MARCEL ROUBAULT

France

AU cours de sa magistrale communication intitulée “ *Nature of metasomatism in the processes of granitization*,” le Professeur P. Eskola a montré que, par des processus purement métasomatiques, on pouvait aboutir à des granites dont la composition est identique à la composition de granites magmatiques. Mais après avoir ainsi apporté une large contribution à la thèse des “ métamorphistes ” il a présenté un plaidoyer éloquent en faveur des magmatistes et de l'idée de magma.

Ainsi donc, une fois de plus, les pétrographes se trouvent devant l'idée de l'existence de deux catégories de granite. Le problème a été déjà posé par le Professeur H. H. Read dans ses “ *Meditations on granite* ” dont un paragraphe est intitulé “ granite and granite.”

Je n'ai pas l'intention de présenter une communication supplémentaire n'ayant pas été inscrit dans l'ordre du jour du Congrès. Mais, grâce à l'extrême amabilité du Professeur et de Madame Holmes (Doris Reynolds), je voudrais simplement présenter une suggestion en vue de l'orientation des travaux du prochain congrès.

Lorsque l'on examine les différentes théories émises pour expliquer la formation du granite on constate que les métamorphistes sont parvenus à une conception logique de la formation des roches granitiques. Et les connaissances de plus en plus nombreuses aujourd'hui acquises sur les réactions et diffusions dans les milieux solides permettent en outre de donner une explication satisfaisante des phénomènes observés.

D'autre part, du côté des magmatistes on constate que de nombreuses théories ont été émises pour expliquer la genèse du granite à partir d'un magma fondu. La plus cohérente de toutes est celle de la “ crystallization-differentiation ” du Professeur N. L. Bowen. Comme l'a si bien dit le Professeur P. Eskola cette théorie a fait époque “ for petrology, bringing our science for the first time upon a firm physico-chemical foundation.” Mais hélas la théorie de la crystallization-differentiation elle-même n'est pas parvenue, à beaucoup près, à donner une explication des phénomènes observés.

Pour comprendre l'attitude des pétrographes dans cette discussion il est nécessaire d'étudier l'évolution historique des idées sur le granite. Indépendamment les uns des autres, René Perrin et moi-même en 1939, H. H. Read en 1942, avons fait cette étude. Que constate-t-on lorsqu'on examine les intéressantes discussions du passé? On constate que derrière toutes les discussions, derrière toutes les tentatives d'explication, il y a en définitive la persistance de la foi en un véritable dogme. Et ce dogme remonte à l'époque célèbre où James Hutton émit le premier l'idée de la nature plutonique du granite en tirant argument de l'observation des filons du granite du Glen Tilt. On conçoit très bien qu'à la fin du 18ème siècle “ igné ” et “ fondu ” aient pu paraître deux synonymes ; mais il me semble tout de même que depuis 150 ans la physique et la chimie ont fait quelques progrès.

Le temps passe, les arguments présentés par les métamorphistes demeurent souvent sans réponse scientifique—mon ami R. Perrin et moi-même en avons fait l'expérience depuis dix ans—et l'idée ancienne de magma demeure. “ Oui, mais il existe des filons de granite ” répondent néanmoins parfois les magmatistes comme argument suprême, sans d'ailleurs se compromettre par des explications détaillées.



Telle est la raison pour laquelle je suggère à tous les pétrographes du monde ici présents de bien vouloir porter à l'ordre du jour des délibérations du prochain congrès la question capitale des Filons du Granite et du cortège des roches associées, pegmatites et aplites.

Cette question est extrêmement complexe et des auteurs ont déjà montré que, dans bien des cas, les "injections filoniennes" ne sont qu'apparences. Personne par exemple n'a encore donné, dans l'idée magmatique, d'explication correcte des injections "lit par lit."

Le moment paraît donc venu, pour les "magmatistes" d'exposer aux "métamorphistes" les arguments décisifs et scientifiques que l'examen des filons comporte à leur avis.

Sans doute certains penseront-ils que cette façon de poser le problème des filons prend un peu l'allure d'un défi, en un combat d'ailleurs bien pacifique. Mais le Professeur Eskola lui-même n'a-t-il pas comparé ironiquement les "métamorphistes" aux enfants qui veulent rejeter l'eau de leur bain. Etant moi-même un de ces enfants je proclamerai tout d'abord un certain droit à obtenir pour le bain une eau au moins claire.

J'ajouterai en outre que le débat que je souhaite sur les filons donnera, je l'espère, aux avocats de l'Ecole magmatiste, l'occasion de nous expliquer d'autres faits qui se relient à la même question. Je souhaite en particulier entendre une explication satisfaisante de la formation des cristaux isolés de feldspaths, identiques à ceux du granite et situés hors du granite, dans la roche encaissante. Je le souhaite d'autant plus que le Professeur Eskola cite le granite Rapakivi comme exemple de véritable granite magmatique ; n'est-ce pas pourtant ce célèbre granite dont les non-moins célèbres cristaux de feldspaths zonés, situés dans le granite et hors du granite, ont donné lieu à tant de discussions ?

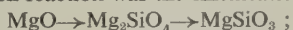
De plus en plus, vraiment, je songe à l'incrédulité du Duc de Wellington, si justement évoquée par H. H. Read.

#### DISCUSSION

L. GLANGEAUD demande si les questions posées à un Congrès doivent être déterminées dans le Congrès précédent. M. Glangeaud pense qu'il ne faut pas confondre le problème de la granitisation avec le problème complètement différent des intrusions plutoniques et hypabyssales.

R. F. YUELL (who had acted as Steward to the Meetings of Section B) said that Professor Roubault's contribution and many of the papers read in Section B, especially that by Dr. Reynolds, seemed to show that geologists were now facing a problem similar to that which had faced chemists about fifteen or twenty years ago. It seemed that geologists were divided into two camps on the question of the formation of granite by the granitization of a more basic rock. Just so were chemists divided on the question of reactions between solids. One school, that of Hedvall and Jander, held that a reaction between two solids occurred by the diffusion of one into another without any melting. The other school, that of Balareff, held that a new solid could be formed only by the fusion of the constituents. The solid diffusion school were eventually proved correct.

One such reaction was the silicification of periclase when surrounded by a mass of silica :



this occurred at temperatures far below any possible eutectic melt. Recent work in the Chemistry Department of the Imperial College had confirmed the solid diffusion theory in this system, and slides belonging to Professor Brammall had shown the various stages of the process in action, so to speak. It was significant that most reactions of that type involved  $\text{SiO}_2$  and silicates. It seemed possible that in large scale geological phenomena a similar process had been at work. Admittedly the masses concerned were far larger, but the time available was also correspondingly long. It seemed that granitization of basic rocks might, by analogy, be due to their being surrounded by a mass of silica-rich rocks, followed by solid diffusion until the original rock had its silica content raised to that required for granite. The formation of large crystals was possible, without formation of magma, by a sintering process. Problems of this type, on the borders of geology, physics and chemistry, provided an interesting study, and a higher degree of co-operation between the three sciences would certainly lead to fruitful results. Geologists had often to rely, willy-nilly, on chemical data, phase diagrams, etc., which were by no means reliably established. For example, recent work in the Chemistry Department referred to had indicated that the silica phase relations might be in error in several particulars.

**LE BATHOLITE GRANITIQUE DE DUVERNY  
(NOUVEAU QUÉBEC, CANADA)  
ET SON CORTÈGE DE ROCHES ASSOCIÉES : CONTRIBUTION A L'ÉTUDE  
DES CARBONATITES**

**Par E. BRUET**

**France**

**ABSTRACT**

Le batholite granitique est associé avec : granodiorites, micro-granites, basaltes, gabbros. Dans l'auréole, on observe d'abord une granulation métamorphique, puis une carbonatation des roches par la dolomite. Lorsque des dykes de carbonate sont coincés dans le granite vers sa périphérie, il y a pénétration de la dolomite dans le granite encaissant et la démolition des feldspaths amène notamment la formation d'albite néogène. La biotite cède devant la dolomite après le stade chlorite. Basaltes ou gabbros sont envahis par la dolomite. Les plagioclases sont corrodés et la dolomite prend place à la faveur de la saussuritisation des feldspaths dans la granodiorite et de l'ouraltisation des pyroxènes dans les basaltes.

Les greenstones de l'auréole sont touchés par la dolomitisation, suivant les synclinaux ou anticlinal. Dans les roches volcaniques anciennes, on voit de fin métacristaux de dolomite qui tendent à remplacer l'ancienne structure sans l'épigéniser ; les cristaux anciens et nouveaux n'ayant pas la même orientation. Les métacristaux de dolomite sont des bâtonnets avec macles polysynthétiques, des rhomboèdres ou des scalénoèdres avec macles par accollement et par interpénétration. Tous apparaissent, par rapport à l'ancienne structure, comme des étoiles sur un fond nuageux. On s'efforce de déterminer l'âge des formations et on insiste sur le caractère *deep seated* des greenstones carbonatés.

**THE FINAL PETROLOGICAL CONSTITUTION OF THE GREEK METAMORPHIC ROCKS**

**By GEORGE MARINOS**

**Greece**

**ABSTRACT**

The metamorphism of rocks in Greece started before the Alpine foldings and continued all through their duration. Parallel to this, successive granites of different types were emplaced. What is considered as regional metamorphism must have affected rocks of different geological ages even up to the Cretaceous flysch. During the foldings the already metamorphic rocks of the depths were folded and translocated to higher crustal levels. As a result they underwent a retrogressive metamorphism and a dynamic metamorphism, corresponding to which they were mineralogically and petrologically transformed. The associated older igneous rocks, basic and acid, underwent the same transformations. During sericitization and saussuritization, etc., of the plagioclase, large quantities of alkalis and silica were freed and became available for migration during the dynamic metamorphism. In this way concentrations of quartz in certain localities and the widespread occurrence of alkali-amphiboles (glaucofan, barroisite, etc.) can be accounted for. The post-tectonic granitic masses and most of the volcanoes of Neogene age are composed of rocks of granodiorite—diorite composition.

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# FORMATION DIAGÉNÉTIQUE DES MINÉRAUX "GRANITIQUES" DANS LES CALCAIRES

Par C. SOROTCHINSKY

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## ABSTRACT

L'auteur décrit les constations nouvelles, faites durant une longue étude au microscope, à fort grossissement, des roches calcaires paléozoïques belges. Ces constatations semblent prouver que :—

- (1) Les *roches granotoides* peuvent se former à la place d'un calcaire, dans les conditions de diagenèse normale ; les minéraux dits "pneumatolithiques" (notamment : quartz, feldspaths acides, micas, zircon, tourmaline, rutile et ilménite)—se forment *au sein des tissus calcaires d'un animal*. Il est impossible de considérer ces minéraux comme détritiques ; d'autre part, la roche calcaire ne montre aucune influence pneumatolithique ou métamorphique, la calcit fibreuse, secretée par l'animal, n'étant pas encore récrystallisée.
- (2) Le *quartz* en mosaïque (typique des quartzites normaux du Paléozoïque) se forme facilement à la place des organismes à test calcaire. La roche quartzitique supposée "sedimentaire," peut, en réalité provenir d'une substitution par le quartz néogène d'une roche originellement calcaire. Nulle trace de cette substitution ne persiste dans la roche.
- (3) La *séricite* et la *chlorite* se forment aisément, dans les conditions de diagenèse normale, à la place de n'importe quelle roche ancienne. Par conséquent, les roches schisteuses paléozoïques (schistes, phyllades, etc.) peuvent provenir d'une *phyllitisation*, assez récente—des roches originellement carbonatées, granitoïdes ou quartzitiques.

## DATE DUE





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- PART XV. Proceedings of the International Paleontological Union.